1989

Plans and specifications for a full-scale towing model validation experiment.

Christensen, Erik Niels.

Monterey, California. Naval Postgraduate School

C44922

PLANS AND SPECIFIATIONS FOR A FULL-SCALE TOWING MODEL VALIDATION EXPERIMENT

by

ERIK NIELS CHRISTENSEN

B.S. Ocean Engineering
United States Naval Academy
(1979)

SUBMITTED TO THE DEPARTMENT OF OCEAN ENGINEERING
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREES OF

NAVAL ENGINEER

and

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
May, 1989

PLANS AND SPECIFICATIONS FOR A FULL-SCALE TOWING MODEL VALIDATION EXPERIMENT

by

ERIK NIELS CHRISTENSEN

Submitted to the Department of Ocean Engineering
on 12 May 1989 in partial fulfillment of the
requirements for the Degrees of Naval Engineer
and Master of Science in Mechanical Engineering

ABSTRACT

The study of the dynamics of tension extremes developed during open ocean towing has been an ongoing project at MIT. Analytical models have been developed to predict the extreme towline tensions based on the theory of "short term extremal statistics" (Frimm, 1987). The U.S. Navy has adopted these models as the technical basis for the prediction of dynamic towline loadings in the U.S. Navy Towing Manual (1988). Although the theory is the most advanced currently available, it has not been validated by full-scale experiment at sea. This study involves the planning of a field test to assess the accuracy and applicability of the these analytical predictions.

An overview of the important design considerations in the planning of a full-scale towing experiment is presented. A discussion of each of the parameters to be measured during the experiment is included with a description of various types of instruments available and their calibration procedures are described. A sensitivity analysis was performed to help identify the relative importance of length, mean static tension, wind speed, and size of towed vessel on the developed dynamic tension in order to define conditions that would have a larger ranges of dynamic tensions. Equipment selection was based on a set of developed measurement specifications.

In conjunction with this study all preparations have been made to conduct the full-scale towing experiment. A data acquisition program has been developed using the Project Athena laboratory computer system and has been interfaced with all sensors at an end-to-end dry run. A test plan has been developed and distributed to all involved personnel. A set of analytical predictions is presented for various wind speeds, mean tension levels, and hawser lengths which can be used on-scene for data analysis. The experiment is now scheduled to be conducted off the coast of Oahu, Hawaii in early May 1989 with the USS SALVOR (ARS 52) towing the ex-USS HECTOR (AR 7). Complete data analysis and comparison with the analytical model will be conducted post-voyage and the results detailed in a supplementary report to be published upon completion of the experiment.

Thesis Advisor: Jerome H. Milgram
Title: Professor, Department of Ocean Engineering

Acknowledgements

I would like to express my sincere appreciation to both Professor Jerome Milgram, my thesis advisor, and Dr. Fernando Frimm, my thesis supervisor, for their guidance and advice during the course of this study. A special word of thanks to Fernando for the countless hours spent discussing the finer points of towing dynamics. His enthusiasm and dedication were major factors in the success of this undertaking.

I would also like to thank CAPT Charles Bartholomew, USN, Mr Dick Asher, and Mr Bob Whaley of the Office of the Supervisor of Salvage and Diving (NAVSEA OOC). Without their administrative assistance and financial support, this project would never have been realized.

Finally, but certainly not last, I would like to express my gratefulness and deepest thanks to my wife Darlene, for her patience, companionship, understanding, and willingness to "endure" three years in New England!

Table of Contents

List of Figures

List of Tables

Chapter One

Introduction

1.1 Towing System Model

A tug towing another vessel at sea represents a twelve degree of freedom (DOF) system which can be modeled as two masses separated by a non-linear damped spring. Since ship response is a function of individual hull characteristics, each vessel moves distinctly and separately in surge, sway, heave, roll, pitch, and yaw in reaction to both surface waves and towline tensions. These seakeeping motions force the end points of the towline to move and the resulting hawser elongations produce dynamic tensions.

Because of the stochastic behavior of ship motions, a deterministic description of dynamic cable elongations is not adequate to determine tensions. Since the occurrence of tension extremes are rare events, it would be impractical to attempt to directly evaluate them from time simulations of cable tensions experienced during dynamic motions. Instead, the method of "short term extremal statistics" can be applied. This approach evaluates the extreme tension (T_{ext}) that has the probability of 0.1% of being exceeded in one day of towing in a specified sea condition (Frimm, 1987).

Experience has shown that the wave elevation in an irregular seaway can be well represented as a Gaussian process. Model tests have confirmed that the non-linearities in ship response in "moderate" irregular seas can be ignored and ship response assumed to be linearly proportional to the wave amplitude (Bhattacharyya, 1978). During towing, these seakeeping motions combine to cause elongations in the towing hawser. Therefore, hawser elongation can be modeled as a Gaussian random process.

However, tension, which is a function of hawser elongation, must be treated as a non-Gaussian random process due to the non-linear relationship that exists between tension and elongation. One aspect of this non-linear behavior is shown by the hawser's static tension versus elongation curve (figure 1.1). At low mean tension levels, below the "knuckle" on the curve, the towing hawser has a large catenary shape and acts like a damped spring. By changing the geometry of its catenary, the hawser is able to absorb changes in elongation with only slight variations in dynamic tension. However, at higher mean tension levels, above the "knuckle," the hawser has little or no sag in its catenary shape and further hawser extension is accommodated by elastic stretching which results in large dynamic tensions.

In addition to the above properties, the dynamics of submerged hawser tensions are influenced by other non-linearities. Since towing hawser elongation constantly changes as each ship moves, transverse motions are developed along the length of the hawser. The viscous cross-flow drag force resulting from these motions can impact significantly on the dynamic tension. The viscous cross-flow drag force (F) is a function of water density (ρ_w), length (l), local fluid velocity (U) and drag coefficient ($C_D(Re)$) and can be approximated as:

$$F = \tfrac{1}{2}\rho_w l^2 U\,|\,U\,|\,C_D(Re) \tag{1.1}$$

Since the cross-flow drag force is proportional to the square of the local fluid velocity, the effects of cross-flow drag are minimized at low cable motion frequencies and the towing

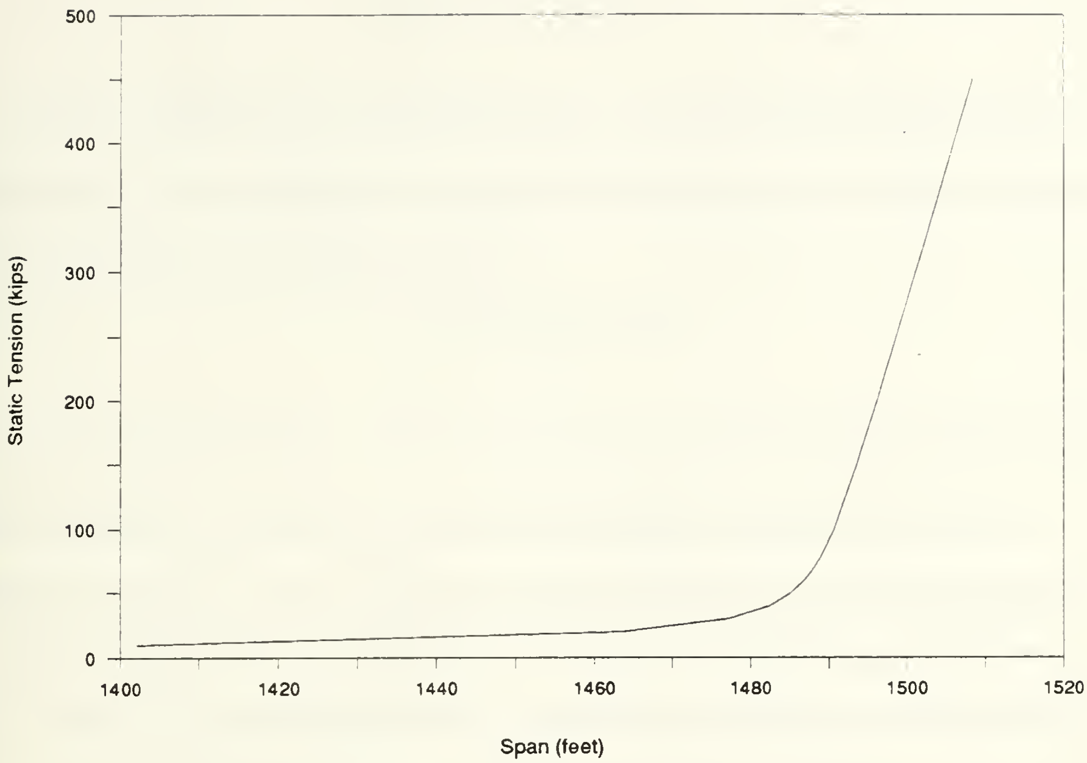

Figure 1.1 Typical Towing Hawser Static Tension versus Elongation Curve

hawser will respond to elongations according to the static tension versus elongation curve described above. However, at higher cable motion frequencies, the cross-flow drag can dominate the inertial forces and, in the limit, completely immobilize the hawser. Thus, even with a large catenary, hawser elongations may be accommodated through elastic stretching (Milgram, 1988) which greatly increases the magnitude of the dynamic tension.

1.2 Towline Tension

The total tension (T_{tot}) developed in a towline during towing contains one steady (T_1) and two dynamic components (T_2 and T_3) which can be expressed as:

$$T_{tot} = T_1 + T_2 + T_3 \tag{1.2}$$

The steady component of the towline tension (T_1) has three distinct parts; the steady tow resistance (R_t), the hydrodynamic drag on the towline (R_{wire}), and the vertical component of the wire weight (T_v) and can be expressed as:

$$T_1 = \sqrt{(R_t + R_{wire})^2 + T_v} \tag{1.3}$$

The steady tow resistance (R_t) is a function of hydrodynamic hull resistance, hydrodynamic propeller resistance, wind resistance, and sea state resistance. Except for the sea state resistance at slow speeds, well established analytical methods exist for accurate prediction of this component of tension. The hydrodynamic resistance of towline (R_{wire}) is a function of the size, length, and geometric shape of the towline which are dependent on the specific tug and the actual towing speed. Estimates of R_{wire} for all towlines in use by the U.S. Navy are presented in the U.S. Navy Towing Manual (1988). The vertical component of the towline tension (T_v) represents the weight of the towline forward of the catenary point and can be approximated by the in-water weight of one half the scope of the towing hawser.

The dynamic tensions developed in a towline are comprised of low frequency and fast dynamic tensions. The low frequency component of towline tension (T_2) is caused by both slowly-varying surge motions and "side slip." The added resistance of the towline creates an exciting force on the two ships which exhibits a low frequency behavior due to its quadratic dependence on the wave amplitude. "Side slip" refers to a special form of yawing motion that is commonly experienced while towing in which the towed vessel slowly swings from side-to-side relative to the centerline of the tug. This is a low frequency term because the period of these motions is on the order of minutes. The fast dynamic tension component (T_3) is the result of wave induced seakeeping motions of both vessels. It is a random process with

typical periods of 4 to 30 seconds. For extreme tension calculations, T_3 can be the singularly most important component of the towline tension as its magnitude can be larger than all other components combined. Although most shipboard sensors are able to monitor the steady state towline tension (T_1), the two dynamic components (T_2 and T_3) are not easily measured because of their rapidly changing nature. The main focus of this investigation will the be measurement of T_2 and T_3 and the factors that influence them.

1.3 Prediction of Towing Hawser Tension

Since hawser elongation is a function of ship motions, seakeeping theory must be applied to determine the resulting tension in the towing hawser. The well established five degree of freedom (DOF) strip-theory of Salvenson, Tuck, and Faltensen (1970) has been incorporated into the MIT Five DOF Seakeeping Program (Loukakis, 1970) which computes the hydrodynamic coefficients and wave forces for sway, heave, pitch, roll, and yaw. However, surge must be included in this analysis because it is the dominant ship motion influencing hawser extension.

The exciting force, added mass, and damping in surge for both vessels are evaluated using the method proposed by Anagnostou (1987). By assuming that each vessel is only excited by the undisturbed incident wave potential, the Froude-Krylov approximation is used to obtain the wave exciting surge force. Surge added mass is approximated as five percent of the actual displacement of the ship. The surge damping coefficients are evaluated as the slope of the resistance curve at the towing speed with provisions made to account for propeller damping of the tug. Surge can now be coupled with the five DOF system to form a complete six DOF expression for the motions of each vessel. To analyze the entire towing

system, the motions of each ship must be coupled together to form a single 12 DOF system.

However, the complete towing system model must also account for the influence that the towline tension has on motions of the two ships. This requires a coupling of the tension in all 12 DOF. Since ship motions are influenced by towline tension and towline tension is a function of cable elongation, the towing problem becomes a 12 DOF non-linear feedback system. To solve this problem, the method of equivalent linearization has been adopted (Frimm, 1987). This is a valid approximation because the forces and moments on the ship due to the towline are considered small in comparison to the hydrodynamic and inertial forces. The resulting ship motion response can then be used to compute the towline tension extremes using the full non-linear methods.

Analysis of the non-linear behavior of towline tension is based on a set of governing towline equations. They can be expressed as follows (Triantafyllou, 1987):

$$m\frac{\partial^2 q}{\partial t^2} = (\bar{T} + \tilde{T})\left(\alpha + \frac{\partial^2 q}{\partial s^2}\right) - b\frac{\partial q}{\partial t}\left|\frac{\partial q}{\partial t}\right| - \bar{T}\alpha \tag{1.4}$$

with

$$\tilde{T} = EA\left[\frac{p}{L} - \frac{\alpha}{L}\int_0^L q\,ds + \frac{1}{2L}\int_0^L \left(\frac{\partial q}{\partial s}\right)^2 ds\right] \tag{1.5}$$

where:

m = cable mass per unit length

w = cable weight per unit length

q = normal motion along cable

$\bar{T}$ = static tension

$\tilde{T}$ = dynamic tension

α = $\frac{wL}{\bar{T}}$ = catenary stiffness

s = Lagrangian coordinate along the cable

b = $\frac{1}{2}\rho C_D D$ = sectional drag force

ρ_w = water density

C_D = cable sectional drag coefficient

D = cable diameter

E = Young's modulus of the cable

A = cross-sectional area of the cable

p = tangential motion along cable

L = cable length

By applying the Galerkin method with sinusoids as basis functions and Newmark's time integration scheme, these equations will provide a series of time simulations of tension. However, since these equations do not provide a closed-form relationship between the hawser tension and the movement of the endpoints of the hawser, they cannot be used directly for the prediction of tension extremes. Instead, Frimm (1987) proposed a "Numerical Towline Model" to discretely express the non-linear towline tension as a function of cable elongation (ξ) and its time derivative ($\dot{\xi}$). This model provides a polynomial approximation for the non-linear towline tension which can be expressed as:

$$\tilde{T}_{NL}(\xi, \dot{\xi}) = \sum_{m=0}^{3} \sum_{n=0}^{3} a_{mn} \xi^m(t) \dot{\xi}^n(t) \qquad \begin{cases} m+n \leq 3 \\ (m,n) \neq (0,0) \end{cases} \tag{1.6}$$

The coefficients of this equality are determined by minimizing the root mean square error between the numerical model and the time simulations generated by the cable governing equations.

By adopting the method of equivalent linearization for calculating ship motions, the non-linear towline tension is approximated by a spring constant (k_{eq}) and a damping constant (b_{eq}) and expressed as:

$$\bar{T}_L(\xi, \dot{\xi}) = k_{eq}\xi(t) + b_{eq}\dot{\xi}(t) \tag{1.7}$$

The fundamental requirement in applying the method of equivalent linearization is that both the non-linear and equivalently linearized systems have the same cross-correlation function. This requires that:

$$k_{eq}E[\xi(t)\xi(t+\tau)] + b_{eq}E[\dot{\xi}(t)\xi(t+\tau)] = \sum_{m=0}^{3}\sum_{n=0}^{3} a_{mn}E[\xi^m(t)\dot{\xi}^n(t)\xi(t+\tau)] \tag{1.8}$$

The statistics of this elongation response are:

$$E[\xi^2(t)] = R_{\xi\xi}(0) = m_{0\xi} \tag{1.9}$$

$$E[\dot{\xi}(t)\dot{\xi}(t)] = -\left.\frac{d^2R_{\xi\xi}(\tau)}{d\tau^2}\right|_{\tau=0} = m_{2\xi} \tag{1.10}$$

The cable spring and damping coefficients can now be expressed in terms of the coefficients of the polynomial tension model (Frimm, 1987):

$$k_{eq} = a_{10} + 3a_{30}m_{0\xi} + a_{12}m_{2\xi} \tag{1.11}$$

$$b_{eq} = a_{01} + 3a_{03}m_{2\xi} + a_{21}m_{0\xi} \tag{1.12}$$

The equivalently linearized tension represents the "best" approximation to the non-linear tension in the "mean square sense." In other words, the model is optimized for the hawser tensions caused by cable extensions of the order of its RMS (root mean square) value. Thus, extreme tensions are poorly approximated. To properly evaluate extreme tensions, the fully non-linear numerical model (Frimm, 1987) must be used.

1.4 Planned Experiments

The analytical models described above have been adopted by the U.S. Navy as the technical basis for the prediction of dynamic towline loadings in the U.S. Navy Towing Manual (1988). Although it represents the most advanced theory currently available, it has not been validated by full-scale experiments at sea. The focus of this study will be the planning of a field test to assess the accuracy and applicability of these methods. Confirming the validity of these analytical models will provide greater faith in the prediction of extreme tensions. This will not only help to improve towing safety and give operators greater confidence to tow at higher speeds when predictions for extreme tensions are low but perhaps allow also allow for a reduction in the traditional factors of safety used in open ocean towing.

Chapter Two

Planning the Experiment

2.1 System Design Criteria

To obtain the necessary data for analysis of towline tensions, simultaneous measurement at two separate locations (the tug and tow) will be required. The tug will be designated as the primary data collection site. All data collected on the tow will be relayed to the tug on a real-time basis using telemetry.

The selection of equipment for this experiment will be based on compactness, reliability, accuracy, self sufficiency, and having sufficient resolution to provide significant data even when sea conditions are calm. Every attempt to minimize interference with, or dependence upon, installed shipboard systems must be made. Although electrical power is generally readily available on the tug, space is always at a premium which requires the use of compact equipment. The portability of test equipment is of prime concern: it should be designed for quick, drop-in installation and be small enough to allow handling up and down ladders. The equipment must be completely self-contained and operationally tested before installing it on either vessel.

If the tow is to be manned, and both power and space are available, the ideal setup would be to install a laboratory type data acquisition system with an operator in direct com-

munication with the primary data acquisition station operator. However, since it is standard practice for the U.S. Navy to tow vessels unmanned, some form of self-powering, such as batteries or a portable generator, will be required on the tow to operate the electronic equipment. In previous experiments (Campman & DeBord, 1985), one of the major causes for failure was power supply problems. Therefore, hardware designed to operate from batteries must either draw so little current that the battery life span will far exceed the time limit of the experiment or it must be able to power up and down to conserve power whenever measurements are not being made. In addition, a means of recharging the batteries during the experiment must be provided.

2.2 Data Transmission

Data transmission can be either via analog (FM) or digital telemetry. It is imperative that the transmission system not increase the relative error of the measurements above specified limits. Radio interference of data transmission has been a severe handicap in previous experiments (DeBord, Purl, Mlady, Wisch, & Zahn, 1987). Analog systems offer the advantage that raw data can be transmitted and stored. This means that post-voyage analysis is not limited by sampling system constraints. However, analog telemetry is very frequency sensitive and the slightest drift in frequency will translate directly into measurement error. Digital transmission systems, on the other hand, are much more tolerant to finite changes in frequency and signal levels and data can be multiplexed for a large number of channels at low power consumption. However, digital transmission systems are limited by bandwidth constraints. Therefore, since neither system shows a dominant superiority over the other, the final selection of transmission system type should be based primarily on the availability of resources.

2.3 Data Filtering

Data filtering is required to reject the high frequency components of unwanted noise which can introduce distortion or aliasing into the recorded data. Aliasing can be avoided by ensuring that the sampling interval is small enough that the maximum frequency component of the desired signal is less than the upper cutoff frequency.

The first step in determining the upper cutoff, or Nyquist, frequency is to select a sampling interval. It is important to ensure that the Nyquist frequency is high enough to cover the full frequency range of the continuous time series. Since this requires some prior knowledge of the frequency content of the data to be sampled, analytical models can be used to predict frequency spectrums. The Nyquist frequency (f_n) is then determined by the selection of the sampling interval (δt) and can be expressed as:

$$f_n = \frac{1}{2\delta t} \tag{2.1}$$

All data is to be attenuated as needed to provide a ±10 volt input to the data acquisition system. This will allow for uniform resolution sensitivity for each parameter being measured. All signals should have identical filtering to avoid introducing relative phase shifts between data channels.

2.4 Data Recording

All data collected at the main data acquisition site on the tug shall be in digitized form and recorded on diskettes compatible with the IBM-PC standard. This will allow playback and complete post-voyage analysis. A redundancy in the recording of all measurements is

desirable and considered necessary to provide a measure of safety should data transmission problems occur. Therefore, all data measurements on the tow are to be digitized and recorded on a personal computer while being telemetered. The data acquisition equipment should allow active monitoring of data during the designated test interval.

The real-time measurement and recording of data must be dynamic in nature; instrument response times and sampling intervals must be fast in comparison to the motions of the tug, tow, and towing hawser. Digital data is to have 12-bit accuracy and signal amplification is to be used such that the allowed error corresponds to at most three bits.

Data acquisition through all channels must take place in a "burst mode" with one burst occurring each sample period. The maximum time skew between "adjacent" channels is to be 30 microseconds. Since each burst of data will take about one millisecond, the data acquisition system will be inactive for most of the time. The timing accuracy in the data acquisition and recording system is to be within one part in 10,000. Therefore, all data should be recorded on a single device to prevent possible timing errors associated with recording on multiple devices. The system time at the start of each data acquisition "burst" shall be recorded along with the data from that "burst."

2.5 Data Processing

Although most data processing can be accomplished upon completion of the experiment, some immediate analysis must be done to determine if the data recorded is correct and if the results are meaningful. This will require that extensive preparations be done before the experiment so that analytical predictions are available for all scenarios anticipated during the

actual data recording. During the experiment, a computer program must be able to provide average values, power density spectrum for all dynamic measurements, and provide a comparison of measured statistics to the theoretical predictions.

2.6 Test Location

The selection of the most favorable location to conduct the towing experiment is dependent upon several key aspects; the availability of a naval towing asset, the availability of sufficiently large enough vessel to be towed, and the prevailing weather patterns. Although U.S. Navy salvage tugs operate worldwide, they are limited in number as shown in Appendix A. They are concentrated into three main "home ports"; Little Creek, Virginia, San Diego, California, and Pearl Harbor, Hawaii. The availability of one of these vessels to support this experiment is contingent upon their operational schedules as dictated by their local fleet commanders. Generally, these vessels are available only for regularly scheduled tows which would mean that the experiment would have to be conducted on a "tow of opportunity" basis. There are several serious drawbacks to using a "tow of opportunity" vice a "dedicated tow." The installation and conduct of the towing experiment would be of secondary importance and most likely be on a "not-to-interfere" basis. This would place great restrictions on the ability of obtaining sufficient data to examine all factors influencing tension extremes. Since open ocean tows generally last thirty days or longer, there is also the problem of how to disembark the experimenters and equipment at sea upon completion of the experiment without requiring them to remain on the tug for the entire voyage.

The availability of a "towed" vessel that is large enough that measurable dynamic tensions will result is even more difficult to plan. Although the prime choice would be to use an

operational ship, the availability and scheduling of such a ship for a minimum of two weeks (to allow time for installation, testing, and demobilization) is very unlikely and cost prohibitive. A more realistic alternative would involve the use of a barge or decommissioned ship. Using a barge is the least preferred method as the dynamics of its motions could differ greatly from an naval surface combatant. The most likely source of obtaining a vessel to tow would be a decommissioned ship: either incident to a transfer to inactive status or one presently in "moth balls."

Local weather conditions will play a significant role in the outcome of the experiment. In normal tow operations, it is highly desirable to minimize dynamic loadings on the hawser by avoiding weather extremes. However, the opposite is true with this experiment as some extreme weather influences are required in order to obtain a larger range of dynamic tension extremes. The two most significant environmental factors influencing this experiment are the wind speed and "fetch," the horizontal distance over which the wind blows. As will be shown in a sensitivity analysis (chapter 4), relative wind speeds greater than 15 knots are needed to generate measurable dynamic tensions. To identify possible test location sites that meet this requirement, a review of historical synoptic weather patterns along the coastline of the United States was undertaken. Figure 2.1 provides the seasonal variation of the mean wind speeds for the six most logical locations. It should be noted that these are only mean wind speeds and for exact probabilistic determination, their actual frequency distribution should be used. However, the mean values are adequate for comparison of the relative superiority of the one site over another.

Oahu, Hawaii presents the most favorable location for the experiment because of its high mean wind speeds for the majority of the year. In addition, since it is an island, fetch lengths should be very large and hence larger wave heights can be anticipated. Conducting the experiment at several different locations around the isiand would allow measurement of

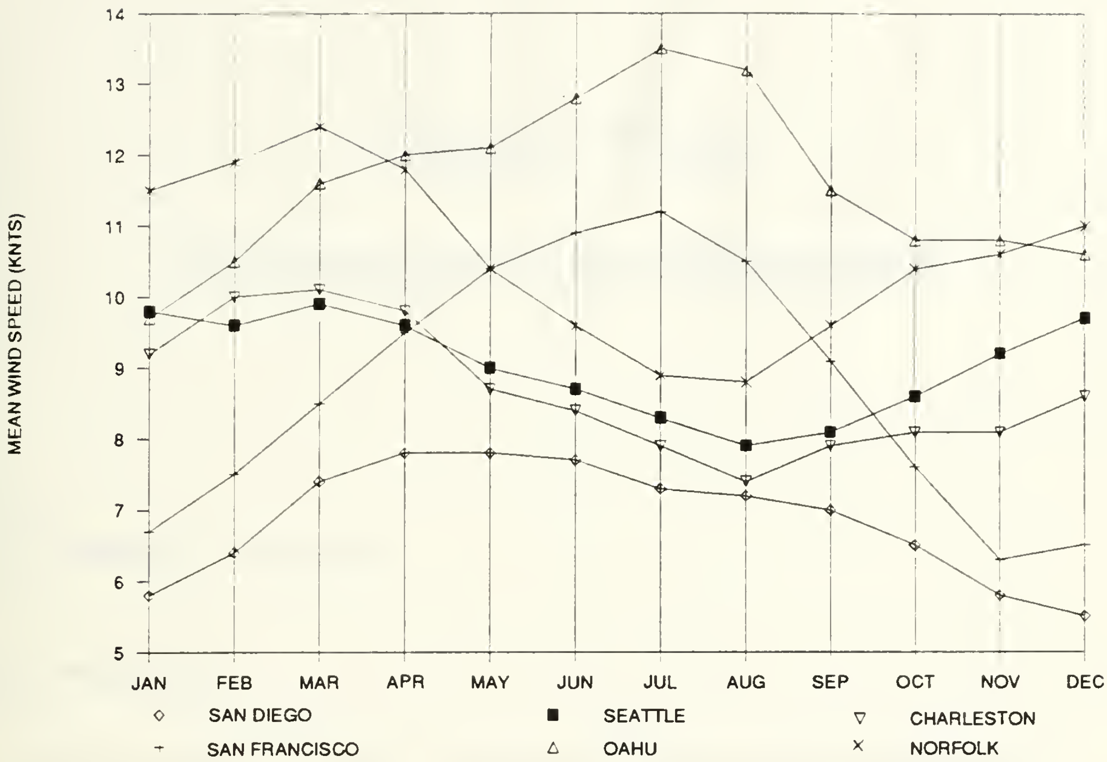

Figure 2.1 Mean Wind Speeds of Selected Sites

dynamic tensions in different sea states since the fetch length on the lee of the island would be significantly less than that of the windward side. Although the Norfolk area has higher mean wind speeds in January through March, the prevailing wind direction at that time of year is from the southwest which would tend to minimize the fetch length. Therefore, strictly from an environmental viewpoint, the most favorable time period for this experiment would be June through August around Hawaii. However, because of time constraints imposed by the deadline of this thesis, an earlier date must be used. Even though the trade winds of Hawaii would not be at their peak, they are considered sufficiently strong to provide measurable dynamic tensions.

Chapter Three

Parameters to be Measured

3.1 Towline Tension

3.1.1 Background

The total tension developed in a towline while towing contains both steady and dynamic components. The installed shipboard sensors on a towing ship are designed to measure only the mean steady tension. Due to their rapidly changing nature, dynamic tensions are not normally measured but are simply accounted for by applying factors of safety to the towline design. However, in order to validate analytical predictions, both the steady and dynamic tension components must be accurately measured.

3.1.2 Sensor

During normal towing operations, a visual display of the towline tension, as measured from an installed tensiometer on the towing machine, is maintained on the tug. However, this sensor should not be used for the towing experiment because neither its calibration nor sensitivity to dynamic loading can be properly guaranteed and confirmed before the experiment without extensive testing. Time permitting, a bollard pull test could be conducted to compare the tension in the load cell to that of the installed tensiometer. However, the

logistics of adding this test would significantly increase the complexity of this experiment and delay the completion of the seakeeping test. Therefore, stand alone tension sensing devices should be used; one on the tug and one at the tow end of the hawser. Typical sensors used for this type of application are tension links containing internally mounted strain gage bridge circuits which produce an output voltage proportional to the amount of strain (tension) developed on the device.

Measurement of the tension at the tug end will be accomplished using a tension link attached directly to the hawser using a carpenter stopper as shown in figure 3.1. The tension link will be secured to a deck padeye on the fantail of the tug using a wire rope pendant. Measurement of tension at the tow end will be accomplished using a waterproof, load sensing clevis pin type tension link which will directly replace one of the standard shackling bolts connecting the towing hawser to the towing bridle as shown in figures 3.2 and 3.3. The load sensing clevis pin employs internally mounted strain gages positioned on a neutral axis plane relative to one specific plane of pin loading. This allows the pin to produce an electrical signal proportional to axial loading.

3.1.3 Calibration

Calibration of the load cells requires laboratory testing using an extensometer or similar device capable of producing large tensions. As both load cells will be factory calibrated before the experiment, no on-site calibration is necessary. Since the towing load will be taken up by the load cell, the ship's installed tensiometer will be inoperative during testing and cannot be used as a redundant source. However, comparison of the readings from both ends of the hawser would help to provide an indication if one should malfunction.

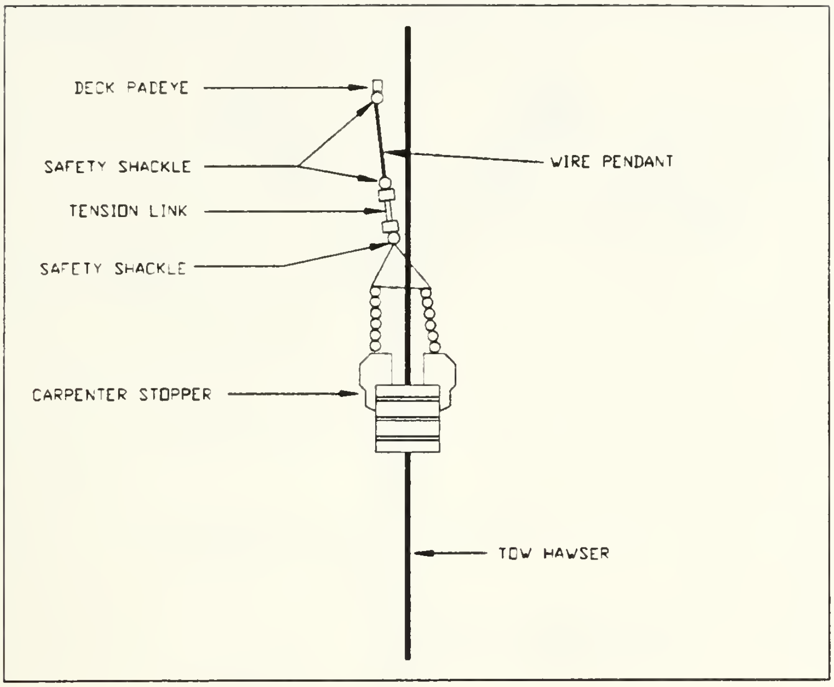

Figure 3.1 Tension Measuring Configuration on the Tug

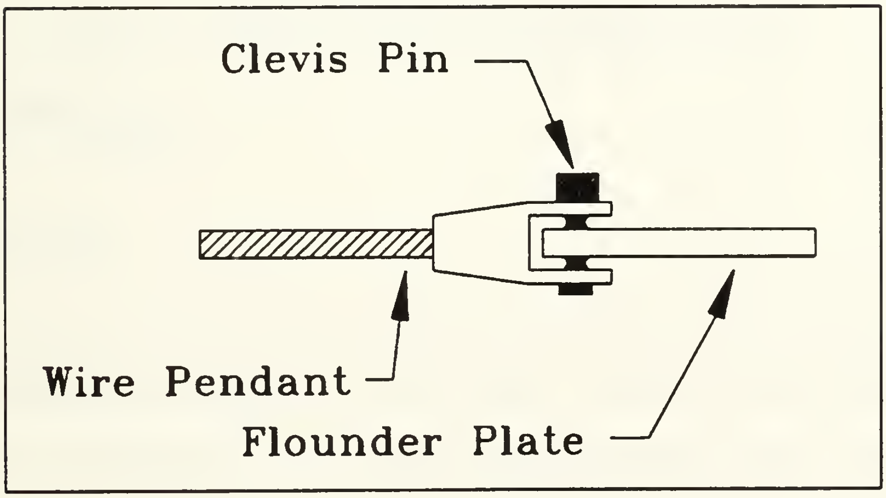

Figure 3.2 Tension Sensing Clevis Pin Installation

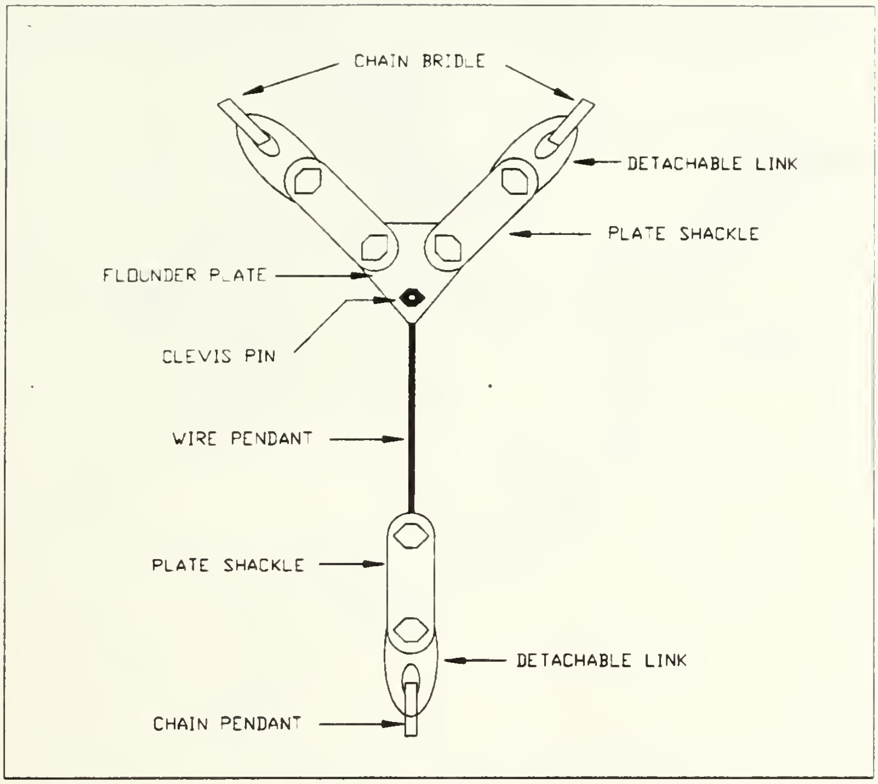

Figure 3.3 Tension Measuring Configuration on the Tow

3.2 Ship Motions

3.2.1 Background

The motions of a ship at sea in a confused, three dimensional sea are very complex but can be broken down into six degrees of freedom relative to three mutually perpendicular coordinate axes. The hydrostatic frame of reference used to describe these motions is an orthogonal, right-handed, "earth fixed" coordinate system (X_o,Y_o,Z_o) where X_o is the direction of mean forward ship motion, Y_o is positive to port, and Z_o is positive vertically up. The angular motions follow the right-hand-rule convention as shown in figure 3.4.

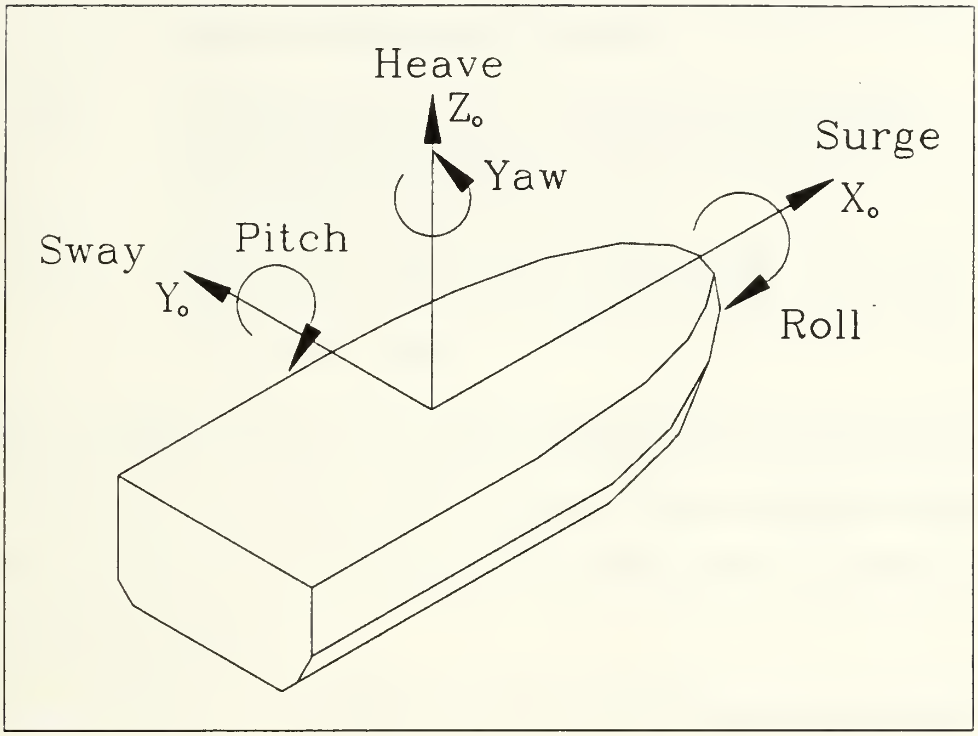

Figure 3.4 Earth Fixed Coordinate System

The motions experienced by a floating body include the three rectilinear motions of surge (x), sway (y), and heave (z) and the three angular motions of roll (φ), pitch (θ), and yaw (ψ) which are defined as follows (Comstock, 1967):

Surge: the longitudinal component of dynamic motion that is horizontal in the direction of forward ship motion parallel to the X_oY_o-plane, positive forward.

Sway: the transverse component of dynamic motion that is horizontal along the Y-axis and parallel to the X_oY_o-plane, positive to port.

Heave: the vertical component of dynamic motion that is perpendicular to X_oY_o-plane, positive up.

Roll: the transverse oscillatory rotation about the ship's longitudinal axis measured from the vertical X_oZ_o- plane to the Z-axis, positive with the starboard side down.

Pitch: the longitudinal oscillatory rotation about the ship's transverse axis measured from the horizontal X_oY_o-plane to the X-axis, positive with the bow down.

Yaw: the angular oscillatory rotation about the ship's vertical axis measured from the vertical X_oZ_o-plane to the X-axis, positive with the bow to port.

Any or all of these motions may coexist at the same time and the resulting superposition of motions is complex and often difficult to describe. Since each ship operates in a six DOF domain, complete analysis of the motion of the towing system will require the solution of 12 simultaneous equations.

During the experiment, a complete time history record of the motions of both the tug and tow in all six DOF is required. Measurements will be made using motion detection devices that contain both accelerometers and gyroscopes. Since the recorded data must be referenced to the earth fixed coordinate system to be consistent with the analytical model, the use of gyro stabilized accelerometers is preferred. However, uncompensated accelerometers can be used if corrections are applied to translate their ship referenced output signals into earth referenced coordinates. Similarly, corrections must be made to the account for the fact that gravitational acceleration varies on the mean axis of non-stabilized accelerometers.

3.2.2 Sensors

For this experiment, two six DOF motion sensing packages, each containing a vertical referenced gyro, capable of measuring pitch and roll, and six servo accelerometers, will be used. The main unit, consisting of a gyro and three accelerometers, will be mounted at the

ship's Center of Gravity (CG). The three other servo accelerometers will be packaged in separate containers and located at known distances from the main unit. They will be capable of measuring angular accelerations directly which will eliminate the need to differentiate the gyro angles to obtain the angular motions. Since the chosen translational accelerometers are not gyro-stabilized, a correction must be applied through software during data recording.

3.2.3 Calibration

All accelerometers will be factory calibrated before installation. Before beginning the experiment, the operational status of all accelerometers must be verified in a complete end-to-end dry run conducted in a laboratory environment. During installation, the signal from each transducer should be verified by manually rotating the sensor to confirm the validity of the output signal. Care must be taken to ensure that the sensors are not placed in a locale that is influenced by structural vibrations which could invalidate their measurements.

3.3 Wave Height

3.3.1 Background

Measurement of the surface elevation versus time is required in order to properly determine the effect of seas on the motions of the ships and the resulting dynamic tensions. The most apparent and often, the most important, waves in the spectrum of waves at sea are those generated by the wind. The characteristics of wind-generated waves depend primarily on the horizontal extent of the water surface over which the wind blows, commonly called "fetch," the wind velocity and duration. Other factors influencing wave height include water depth, bottom friction characteristics, atmospheric stability, and the spatial and temporal variations

in the wind field during wave generation.

Although the wind speed is perhaps the most significant aspect in determining the height of waves, strong winds do not generate high waves instantaneously but require a considerable period to do so. For wind blowing for a given duration or over a certain fetch distance, there is a fixed limit to which the average wave height, period and spectral energy will grow. At this limiting condition, the rate of energy input from the wind to the waves is balanced by the rate of wave energy dissipation due to wave breaking and turbulence. This condition, known as a fully developed sea, is used for the development of many standardized wind wave spectra including the Pierson-Moskowitz spectrum.

3.3.2 Sensor

The measurement of wave height spectra can be accomplished using either a wave measuring buoy or an installed shipborne sensor. Since the motions of the ship will disturb the local wave pattern, the preferred method is to use a stand-alone measuring buoy located a short distance away from the ship. However, this places great restrictions on the maneuverability of the towing ships as the experiment must be conducted in the vicinity of the buoy. The National Oceanic and Atmospheric Administration (NOAA) maintains a series of permanently moored, self-contained buoys strategically located along all coastlines of the United States which could be used for this purpose. Unfortunately, data from an individual NOAA buoy is not available on a real-time basis. These buoys transmit specially coded information directly to the National Data Buoy Center (NDBC) in Bay St. Louis, Mississippi via satellite. This results in a minimum of a three week delay in obtaining data on a specific buoy from NDBC. The other major drawback in using a NOAA buoy is that the operational status of one of these buoys at some date in the future cannot be guaranteed beforehand.

Since the planning of a towing experiment takes months of coordination between different organizations. an alternate and more reliable source of measurement is required in case the NOAA buoy is not operational at the time of the experiment.

One attractive alternative is to deploy a portable buoy, capable of measuring low frequency waves, directly from the ship. Although this method allows greater freedom in the selection of the location to conduct the experiment, it presents its own set of restrictions. The availability of a support craft, which is needed to deploy and relocate the buoy between data collection runs, is very dependent upon the local sea conditions. This could significantly impact on the conduct of the experiment especially considering that it is highly desirable to conduct the experiment in areas of higher sea states. Also, the transmission of data from the portable buoy to the data acquisition system requires either additional telemetry gear or providing a means to record the data locally on tape recorders and then manually retrieving and entering the data into the data acquisition computer.

A second alternative, which presents fewer restrictions on the conduct of the experiment, is a non-contacting shipborne wave measuring device. This type of sensor must have a wide dynamic response as low frequency waves have small accelerations which must be detected in the presence of large, high frequency ship accelerations. One type of shipborne measuring device is a portable microwave radar. The unit records the surface velocity by measuring the Doppler shift in radar transmissions bounced vertically off the sea surface. However, the influence of ship motions on the measured data is now a problem. The velocity of the radar is the lesser difficulty since it can be accounted for by integrating the acceleration of the instrument.

As a ship heaves and pitches, it radiates energy into the water in the form of waves. Waves are also generated as the ship travels through the water. Therefore, unless an on-site calibration procedure is performed, the influence of these ship generated waves will severely

corrupt all wave height measurements. This has been confirmed by Sellars (1967) who found large variations in frequency response due to the influence of the ship's hull on the wave height measurements. In addition to individual hull characteristics, the calibration of these devices is a function of wave encounter frequency, relative heading of the waves, ship speed and the pitching motions of the ship.

The sensor to be used in this experiment, a TSK remote wave height meter, contains an internal, compensated linear accelerometer which decouples the pitching motions of the ship. To minimize the influence of ship generated waves on the actual wave system, the unit will be mounted on a post extending forward of the bow of the ship. For bow mounted instruments, Sellars found the optimum location to minimize variations in the frequency response of the unit to be at a distance of four percent of the length of the ship.

3.3.3 Calibration

The conventional method for evaluation of the performance of a wave measuring sensor is to compare its output with other wave measuring systems. This will involve recording data in the local vicinity of the reference wave height measuring system while steaming at various speeds on different courses relative to the waves. Then, by comparing the measured data with the actual wave height as recorded by the reference system, a calibration matrix can be determined for the specific hull form. For this experiment, recorded data can be compared to NOAA buoy data.

Although the accomplishment of this calibration procedure will extend the time required for the experiment, it is considered essential. Since the waves generated by the tow can be considered to have no influence on the tug, only the tug is required to perform this

procedure. Since there is no real-time feedback from a NOAA buoy, this calibration procedure can be conducted independently from the experiment. However, since the installation of instrumentation is costly and time consuming, it would be more cost effective to conduct these calibration procedures as part of the experiment.

3.4 Wind Speed and Direction

3.4.1 Background

The most significant aspect in wind measurement is the positioning of the sensor. The wrong location can lead to errors large enough to far overshadow any loss in accuracy because of less-than-perfect calibration. A unique and deterministic relationship between calibration factor, wind direction, and gradient does exist and it can only be accurately determined in a wind tunnel experiment which far exceeds the scope of this experiment. However, there are some general guidelines that can be followed to minimize installation errors.

The anemometer and wind vane unit should be placed as high as possible on one of the tug's masts in a position that provides unobstructed wind from all directions. The unit must be above the turbulent separated region near the top of the superstructure or significant errors will result. Since these instruments only measure on the horizontal plane, out-of-plane flows affect both wind speed and direction measurements. An up-wash flow is caused by the superstructure obstructing the wind's flow pattern. Durgin (1975) found that the sensitivity of wind direction measurements to be in error by as much as 10 degrees with a 35 degree up-wash angle. He also found that the wind speed measurements (V_{ind}) differed from the actual wind speed (V_{act}) by the square of the cosine of the up-wash angle (β) as given by:

$$V_{ind} = V_{act} \cos^2(\beta) \tag{3.1}$$

Therefore, except for small angles (less than 10 degrees), it is very important to know the up-wash angle in order to properly correct both wind speed and direction measurements. However, since the up-wash angle is highly sensitive to wind direction and wind tunnel tests are required to calculate it, the best way to minimize its effects is to install the unit as high as possible on the ship's mast, preferably near one of the existing wind sensors.

3.4.2 Sensor

To avoid interference with or dependence on shipboard sensors, the preferred method is to use a dedicated instrument rather than rely on the signal from the tug's wind anemometer and wind vane. To minimize the amount of data telemetered between the two vessels, the tug is the preferred vessel on which to install the sensor.

For wind speed measurement, the most obvious choice is either the classical propeller or cup type anemometer because of their proven reliability at sea. Wind speed transducers are generally AC generators which have spin rates proportional to wind speed. Selection of the specific unit should be based on the following design characteristics: threshold velocity, the velocity at which the unit first starts to spin and at which the unit stops spinning as wind velocity decreases; friction velocity, the velocity by which the true calibration curve is displaced from the ideal one because of bearing friction; and dynamic response, listed as a distance constant.

For wind direction measurement, two types of wind vanes are most commonly used; synchro and potentiometer. Both are influenced by the interaction between the wind vane and anemometer. Propeller type anemometers induce errors in direction measurements due to rotating flow behind the propeller. Cup type wind vanes are usually mounted above the

anemometer on a post which passes through the plane of the cups. Thus, for certain directions, the cups pass through the wake of the supporting vane which introduces errors up to ten percent in their direction readings.

3.4.3 Calibration

Calibration of wind anemometer can be checked by removing the propeller and rotating the shaft of the unit at a known speed. The two parameters needed to describe the calibration of a cup anemometer are the calibration slope (k) and friction velocity (V_f). A linear relationship exists between the actual wind speed (V_w) and shaft rotation which can be expressed as follows:

$$V_w = V_f + k(\text{rpm}) \tag{3.2}$$

Although the calibration slope of a given instrument is generally a constant, its friction velocity often increases during field use. Because of the short duration of this experiment, the known values from the initial factory calibration can be assumed to remain constant during the experiment. A post calibration can be conducted upon completion of the experiment to verify this.

The wind vane transducer uses internal potentiometers to measure the wind direction relative to a reference direction, usually true north. Calibration consists of manually training the unit and adjusting the potentiometer until zero ohms are output when the vane passes through the designated reference direction. During actual testing, comparison with the readings from the installed shipboard sensors can be used as a check. Since NOAA buoys record wind speed in addition to wave height, the calibration of the wind instrument and influence of up-wash angle can be checked during the wave height sensor calibration procedures described in the previous section.

3.5 Ship's Speed

3.5.1 Background

The standard installed shipboard instrument to measure speed and distance traveled through the water is called a "log." The two most common types are the electromagnetic speed log and the pressure tube Pitot log. The electromagnetic speed log uses a solenoid and sensors contained in a housing mounted flush with the bottom of the hull. It operates on Faraday's law of electromagnetic induction; the water moving past the hull in the magnetic field generated by the solenoid induces an electromotive force that is directly proportional to the speed of the ship. The Pitot log, on the other hand, consists of a rodmeter or Pitot tube that extending below hull of the ship. The difference between the dynamic and static pressure is translated into deflection of a diaphragm which is proportional to the square of the ship's velocity. The distance traveled can be computed by electronically integrating the measured analog velocity signal.

Since the operational status and accuracy of the installed unit on the tug is uncertain and to avoid disrupting ship operations, it is preferable to provide a stand alone unit. Since the installation of a shipboard log is very complex and well beyond the scope of this experiment, an alternative method must be used. Possible choices include non-contacting sensors, similar to the Doppler radar used to measure the wave height, or to compute the ship's speed from navigational plots. Based both on the available resources and success in previous experiments, the method of choice for this experiment will be to use a portable LORAN C receiver to record the ship's speed.

LORAN, which stands for "long range navigation," is an electronic system using shore based radio transmitters and shipboard receivers to allow mariners to determine their position at sea. It is a low frequency (100 kHz fundamental carrier frequency with 20 kHz bandwidth) pulsed hyperbolic navigation system operated by the U.S. Coast Guard. A hyperbolic line of position is derived from the difference in arrival time of pulses from two transmitting stations. The position of a ship can be computed by interpolating between hyperbolic lines on a LORAN C chart. Based on the time between successive fixes, the speed of the ship can be computed.

3.5.2 Sensor

The portable LORAN C unit selected for this experiment belongs to the test sponsor, NAVSEA OOC. It has been used successfully in previous experiments. It provides both a digital readout of longitude and latitude, time, LORAN time differences (TD's), latitude and longitude, speed over ground (SOG), course over ground (COG), and an indication of the reliability of the LORAN data. Besides the digital display, the unit has an RS-232 output for direct recording of information onto a file on a computer disk. The unit provides an average reading of the SOG with an accuracy of 0.1 knot. The unit estimates the latitude and longitude from the TD's using a mathematical conversion process that is accurate to within 0.25 nautical mile.

LORAN receivers generally do not update synchronously but rather, output a data stream each time a new fix is computed. This occurs at regular intervals of 8 to 30 seconds which is satisfactory for this experiment. The LORAN uses an averaging process between successive fixes to compute the ship's speed. The interval time is user definable between six seconds and seven minutes. Therefore, the longer the interval between updating, the more accurate the data. Since the tug will be requested to maintain a constant course and speed

during each test run, a record of the average speed during the test is satisfactory. This means that the output from the LORAN can be recorded at a much slower rate than the other, more time-sensitive, measurements.

3.5.3 Calibration

Since the LORAN C unit is fully self-contained and provides a comprehensive self test upon powering up, no special calibration procedures are needed. After pierside installation, the latitude and longitude readings on the unit can be verified with the vessel's known position. During operation, the unit has several built in warning alarms to warn of poor data quality. These include a low signal-to-noise ratio alarm, a cycle alarm to indicate when the unit is not confident that it is tracking the correct ten microsecond cycle of the LORAN pulse, and a blink alarm to warn that the LORAN transmitter is having technical difficulties. Under normal operating conditions, a visual display shows when the unit is receiving a TD in the normal tracking mode. In addition to these warning indicators, all data output can be compared to navigational plot maintained by the bridge team of the tug using the ships installed sensors.

3.6 Heading

3.6.1 Background

To define the geometry of the towing configuration, a record of the time-varying headings of both the tug and the tow with respect to true north is required. This will require the use of a magnetic compass. Since magnetic compasses, whether mechanical or electronic, are sensitive to magnetic fields, any magnetic disturbance near a compass will deflect it from

the proper reading. Therefore, provisions must be made to compensate for both the permanent and induced magnetism of the ship. There are two main corrections that must be applied to magnetic compass readings to obtain the true heading; deviation and variation. Deviation accounts for both the permanent and induced magnetic properties of steel and iron ships. Variation accounts for the fact that the earth's magnetic lines of force do not coincide directly with the geographical meridians.

Permanent magnetism is the result of inherent magnetic properties of steel and hard iron used in construction of the ship. Welding, bending, and twisting of steel during fabrication provides stress which magnetize the ship. Subsequent vibrations by machinery and shocks induced by the sea produce stresses which can alter the magnetic state of a ship. Thus, induced magnetism is dynamic in nature as it varies constantly depending on the location and heading of the ship and the stress the ship has been subjected to.

3.6.2 Sensor

The selection of the sensor to accomplish this is guided by power requirements, the effects of magnetic influence from the metal hull, ease of installment, and required calibration procedures. To avoid interference with ship operations, it is preferable to use a dedicated instrument rather than rely on the tug's installed gyroscope. Since the installed sensors on the tow will not be operational, a stand-alone instrument must be used.

The best instrument for this experiment is an electronic compass, also known as a flux gate compass. It consists of a saturated core around which two coils with opposing polarities are wound. In the absence of an external magnetic field, the coils are balanced with no output voltage. As the ship moves, the magnetic field of the earth changes with respect to the compass. This causes a reinforcing of the field of one coil and a detraction from the other. This unbalanced condition causes the circuit to produce a voltage that is proportional to the

ambient magnetic field. The flux gate compass is lightweight, has no moving parts, exhibits excellent transient response characteristics, and is insensitive to vibrational disturbances which makes it ideally suited for marine applications. It can be powered by either 120 VAC or with nickel-cadmium batteries.

3.6.3 Calibration

Preliminary compass adjustments can be accomplished pierside to minimize the effects of the inherent magnetic properties of steel and hard iron used in construction of the ship. However, since the induced magnetic signature of the ship is dynamic in nature and varies depending on the ship's location and orientation with respect to the magnetic poles, final compass corrections can only be accomplished at sea.

Magnetic compasses calibration is accomplished by comparison to a compass of known deviation through a standard procedure known as "swinging the ship." This involves steaming the ship on various magnetic headings and comparing the compass readings to a reference compass. For this experiment, calibration of the flux gate compasses will be accomplished by steaming the ship in known reference directions and comparing the measured heading with that of the ship's installed magnetic compass. By knowing the deviation of the ship's magnetic compass, the deviation of the flux gate compasses can be computed. Since the tow has no operational power, the tug's magnetic compass will be used as the reference compass for calibration of both flux gate compasses. Simultaneous recordings of the headings from both flux gate compasses and the tug's magnetic compass will be taken. The reading from the tow will be obtained via telemetry on a real time basis. The average from three attempts at each heading will provide a reasonable estimate of the deviation of each flux gate compass for that heading. Although this will only be a "pseudo" calibration procedure, it is accurate enough for purposes of this experiment as we are mainly interested

in the time-varying changes in the headings of both vessels while towing. To detect if the tow has a steady yaw angle, which would seriously affect the calibration procedure, a continuous measure of the angle between the centerline ob both ships must be maintained. This can be accomplished using the installed flux gate compass on the laser range finder, which is discussed in the following section.

3.7 Distance

3.7.1 Background

A measure of the time history of the separation between the tug and tow is required to define the geometry of the towing configuration. The use of the tug's installed radar system is unsatisfactory for several reasons; its dynamic response is unknown, radars have a "blind spot" directly astern, and the desire to minimize dependance on shipboard sensors. Instead, a stand-alone portable range finder capable of operating from an unstable and moving platform should be used. Although this poses significant problems to conventional range finders, a laser range finder, which uses very short measurement intervals, can easily accommodate an unstable platform.

A laser range finder houses an internal electrical pulse generator that energizes a semiconductor laser diode which, acting as an optical transmitter, emits infrared light pulses. Using optics, these pulses are concentrated and transmitted. The reflected signal from the target passes through a reception lens and strikes a photo diode generating an electrical reception signal. The range between vessels is computed based on the time between the transmission and reception using a quartz-stabilized clock frequency. With a knowledge of

the exact location of both the laser and its reflector on each vessel, the actual distance between the two ships at any given instant can be computed using trigonometric relationships.

3.7.2 Sensor

The instrument of choice for this measurement is a portable laser range finder with direct computer interface. The selected unit is roughly the size of large pair of binoculars (14" x 9.4" x 3.3") and weighs 8.4 pounds. It has a measuring time of 0.25 seconds with a 0.5m resolution. The unit must be manually trained on the target using an integrated telescopic lens. The distance to the sighted object is immediately displayed in the field of view and simultaneously output to the data acquisition unit. Although the unit has a base range of 820 ft., it can be extended to 26,250 ft. by installing a reflector on the bow of the tow. The maximum range anticipated in this experiment will be 2,100 ft. The selected unit has been modified to operate on 120 VAC and contains a flux gate compass to provide bearing.

3.7.3 Calibration

Calibration of the laser range finder can be accomplished quickly and accurately pierside by placing a reflector at a known measured distance from the laser and verifying its readings. The unit has adjustment knobs for both zero and long range calibration. The installed flux gate compass can easily be calibrated by comparison with the ship's magnetic compass while steaming on different courses in the same manner described in section 3.6.

3.8 Hawser Angles

3.8.1 Background

A measure of the relative heading, both vertically and horizontally, of the towline from the centerline of both the tug and tow is required to properly define the geometry of the towing configuration. Since this parameter is not normally measured during towing operations, no installed shipboard systems will be present. Because of the slow, time-varying nature of "side slip," the measurement of this variable is simplified.

3.8.2 Sensor

The vertical and horizontal angles at each end of the hawser will be measured using two spring-loaded, string-type potentiometers connected directly to the towing hawser. Changes in the length of the string are translated directly into an electrical signal which can recorded on the data acquisition unit.

3.8.3 Calibration

The accuracy of the string potentiometer is largely a function of correct positioning. Although the hawser angles will be determined using trigonometric relations, it is vitally important that the installation of the device be done correctly and with close tolerances.

Chapter Four

Sensitivity Analysis

4.1 Background

Current towing design and operational procedures are based strictly on the mean static towline tension. Dynamic tensions are accounted for solely by applying factors of safety to the static tension. Since both analytical predictions and full-scale towing experiments have shown that the dynamic tensions can be the same order of magnitude as the mean tension, a better understanding of the nature of dynamic tensions is needed. Although the static towline tension is primarily a function of tug power and the tow resistance characteristics, the factors influencing the dynamic tension are not as well defined. Using the equivalently linearized theory, dynamic tensions are considered to be primarily a function of towline extension and its time derivative (equation 1.6).

Although in normal towing operations it is highly desirable to minimize towline tensions, during an instrumented validation experiment it is essential that there are measurable differences between the mean and dynamic tension. To be able to preselect conditions in which a higher range of dynamic tensions can be expected, a better understanding of the parameters that influence towline extension is needed. This was done by performing a series

of time-domain computer simulations. By varying only a single parameter on each successive iteration, the individual effects of each parameter on the resulting dynamic tension were identified.

Because towing operations are conducted at different hawser lengths and changing the hawser scope is a simple process, five different lengths between 1000 and 2100 feet were considered. To gain a better appreciation for the influence that sea conditions have on the dynamic tension, four different sea states were simulated. To investigate the influence of mean static tension, four mean tensions between 10 and 80 kips were simulated. Finally, to assist in specifying the size of tow required for the experiment, both a small and a large ship were considered in the analysis.

4.2 Methodology

The chosen baseline tug was the ARS 50 "Safeguard" Class salvage ship, the newest towing and salvage ship in the U.S. Navy inventory. To assess the effects of the size of the towed ship on developed dynamic tension, two different sized tows were used. The FFG 1 "Brooke" class guided missile frigate was chosen as representative of a "small" ship and the LHA 1 "Tarawa" class amphibious assault ship (multipurpose) was chosen as a "large" size ship. A description of the vessels used in this analysis is provided in table 4.1.

The tug and tow were modeled as being connected with a 2.25 inch wire towing hawser shackled to a towing bridle with one shot of 2.25 inch Di-Lok chain as shown in figure 4.1. The characteristics of the towline are provided in table 4.2.

Table 4.1 Characteristics of Vessels in Sensitivity Analysis

	ARS 50	FFG 1	LHA 1
Length (LBP)	240 ft	395 ft	778 ft
Beam	52 ft	44 ft	106 ft
Draft	15.5 ft	14.5 ft	26.4 ft
Displacement	2,850 Lton	3,200 Lton	40,000 Lton

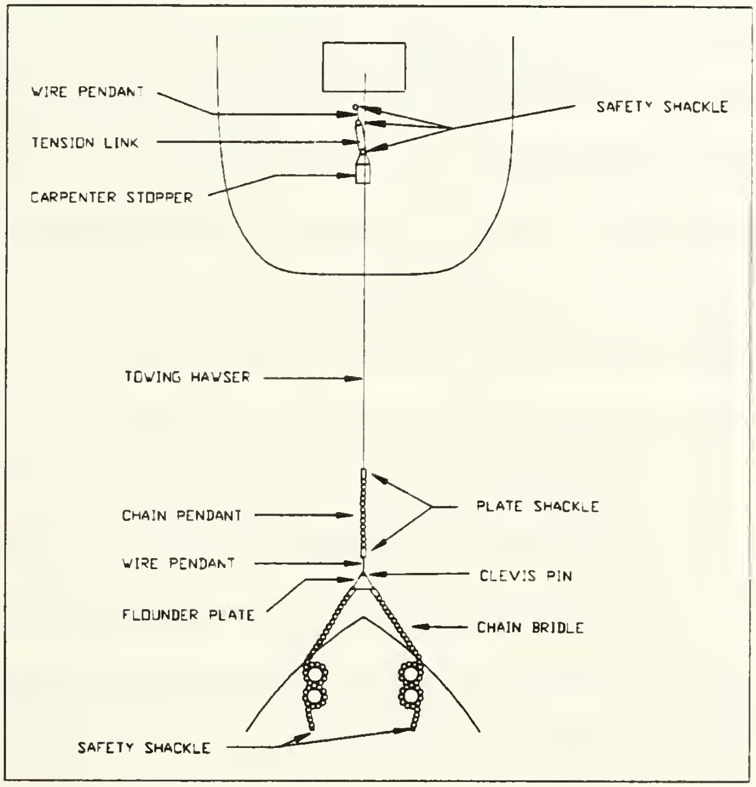

Figure 4.1 Towline Configuration

Table 4.2 Characteristics of Towline in Sensitivity Analysis

	Wire	**Chain**
Type	6x37 IWRC (EIPS)	Di-Lok
Length	1000 - 2100 ft	70 ft
Size	2.25 in	2.25 in
Elastic Modulus	12.6×10^6 psi	30.0×10^6 psi
Weight in water	8.31 lbs/ft	43.5 lbs/ft
Cross Sectional Area	2.35 in^2	7.85 in^2
Breaking Strength	444.6 kips	549 kips

The theory for dynamic towline extension and extremal statistics developed at MIT was then applied to these ships. The ARS 50 was modeled towing at a speed of three knots in head seas. Since values for added resistance have only been developed for stationary vessels and since towing at high speeds is impractical, a speed of three knots was chosen as the most realistic towing speed that also closely approximates zero Froude number. Heading seas were chosen to be the most common encountered while towing at higher sea states, because, as the sea state increases, the tug and tow will generally be forced to head into the seas. The Pierson-Moskowitz sea spectrum was used to simulate wind speeds varying between 15 and 30 knots. The use of unidirectional sea states was considered a valid approximation since the resulting extreme extensions and tensions have been found to differ only slightly from those of directional spectra (Milgram, 1988). Thus by using unidirectional fully developed seas, wind speed may be used to specify different sea conditions.

Since surge is the primary motion influencing hawser elongation, it was the only ship motion considered in the time-series simulations. Errors resulting from the neglect of the influence of the other motions on the dynamic tension are considered unimportant for this

analysis. The two exciting forces were considered to be the Froude-Krylov surge force and added resistance. They account for both high and low frequency forces which cause fast and slow surge motions on the two ships.

The initial step in the time-series evaluation was to model the surface wave surface elevations $\zeta(t)$ as a function of the input amplitude spectrum $S(\omega)$ (Comstock, 1967):

$$\zeta(t) = \sum_{i=1}^{N} \zeta_i \cos(\omega_i t + \varepsilon_i) \tag{4.1}$$

where:

$$\begin{aligned}
\zeta_i &= \sqrt{2S(\omega_i)\Delta\omega} = \text{wave elevation amplitude} \\
N, \Delta\omega &= \text{number and interval of frequency subdivisions} \\
S(\omega_i) &= \text{input amplitude spectrum (Pierson-Moskowitz)} \\
\varepsilon_i &= \text{random phase uniformly distributed between 0 and } 2\pi
\end{aligned}$$

The first order, high frequency excitation force $F_{FK}(t)$ was similarly modeled:

$$F_{FK}(t) = \sum_{i=1}^{N} |F_K(\omega_i)|\, \zeta_i \cos(\omega_i t + \varepsilon_i + \phi_i) \tag{4.2}$$

where:

$$\begin{aligned}
F_K(\omega_i) &= \text{Froude-Krylov surge exciting force} \\
\phi_i &= \text{phase difference between Froude-Krylov surge force and} \\
&\quad\ \text{surface elevation at each frequency}
\end{aligned}$$

The second order, low frequency excitation force $F_x^{surge}(t)$ was similarly modeled as the added resistance of the ships in waves. The added resistance represents the increase in hull resistance as compared to calm water conditions caused by the interaction of the waves with the hull. The added resistance operator, $R(\omega)$, which can be expressed as a function of wave frequency, is proportional to the square of the wave amplitude, thus generating a low fre-

quency exciting force. The work of Kim and Yue (1989) was adopted to approximate this second order, slowly-varying surge drift exciting force as a function of the wave elevation ζ and the added resistance in waves, $R(\omega)$:

$$F_x^{surge}(t) \quad = \quad \sum_{i=1}^{N} \sum_{j=1}^{N} \xi_i \xi_j R(\omega_i) \cos[(\omega_i - \omega_j)t + (\varepsilon_i - \varepsilon_j)] \tag{4.4}$$

The surge motions resulting from these two exciting forces were coupled with the Numerical Towline model (equation 1.6) to generate a time-series of dynamic tensions. To more realistically identify the conditions in which significant dynamic tensions could be expected, the different cases were compared based on the root mean square (RMS) value of dynamic tensions. To better illustrate the relative magnitude differences between the mean and dynamic tensions, all figures are presented in non-dimensionalized form with the RMS dynamic tension divided by the mean tension.

4.3 Influence of Cable Length

As shown in figure 4.2, the RMS dynamic tension developed in a towing cable decreases as length is increased. This can be explained by analysis of the geometry of the cable. As the length of cable is increased, there is less restoring force present in the hawser. This allows the ships to move more in response to wave excitation and hawser tension. The cable is now said to have a "softer" spring constant as the additional sag in the catenary will allow the hawser to absorb these larger elongations without a large increase in dynamic tension. Cross-flow drag, which has been found to increase the non-linear tension under certain circumstances (section 1.1), also adds to the damping of the whole 12 DOF system.

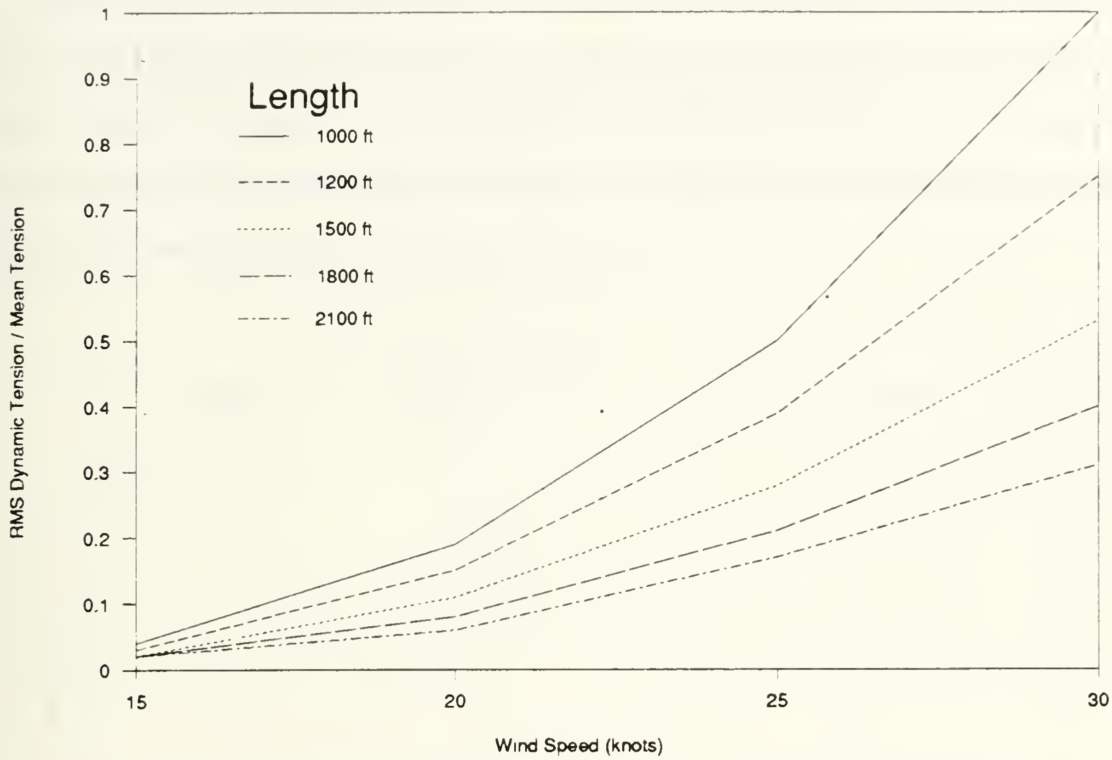

Figure 4.2 Influence of Cable Length (LHA at 40 kips mean tension)

Although cable tension is affected by cross flow drag and other non-linearities, the major influence on it is the nature of the static tension versus elongation curve (figure 1.1). Since this curve does not account for any dynamic effects, it defines the lower bound on the extreme tension. Cable stiffness is defined as the local slope on the static curve at a given mean tension. Stiffer geometry configurations have greater slope which, for the same amount of extension, result in larger tension increases. For very large static tensions, when the cable elongation enters the purely elastic region (above the "knuckle"), the slope remains constant and the static spring constant (K_{static}) can be expressed as a function of cross sectional area (A), modulus of elasticity (E) and length (L) as:

$$K_{static} = \frac{AE}{L} \tag{4.5}$$

Figure 4.3 presents the static curves for three different lengths of the ARS 50 hawser. As hawser length increases, the static curve is displaced to the right and the range of the "catenary" region is extended. Similarly, for the same value of static mean tension, the local slope of the curve decreases with increased hawser length. This further illustrates the effect that increasing length has on decreasing hawser stiffness.

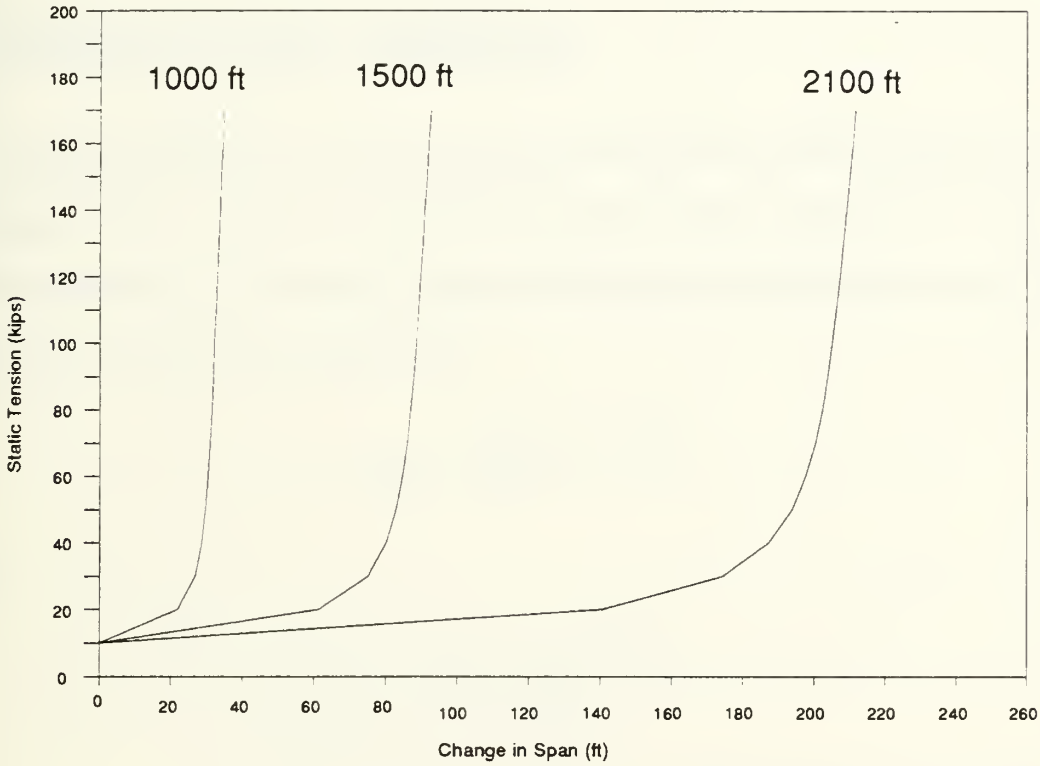

Figure 4.3 Static Tension versus Elongation Curve for ARS 50

The local sea conditions, as related to wind speed, influence the magnitude of the dynamic tension developed at different cable lengths. At lower wind speeds, the dynamic cable tensions become increasingly more insensitive to changes in length. However as wind speed increases, changes in length have significant impact on the dynamic tensions developed which can vary by as much as the magnitude of the mean tension. All lengths of cable

investigated (1000 to 2100 feet) appear acceptable for use in this experiment. However, based on the above analysis, it appears that if lower wind speeds are encountered, the experiment should be conducted with shorter scopes of towing hawser so that a larger range of dynamic tensions will be measured.

4.4 Influence of Sea Conditions

As shown in figure 4.4, the dynamic tension developed in the towline increases as the wind speed increases. This can be explained by analysis of the exciting forces. A semi-empirical expression for the frequency spectrum ($S(\omega)$) of the fully developed waves, known as the Pierson-Moskowitz sea spectrum is:

$$S(\omega) = \frac{0.0081 g^2}{\omega^5} e^{-0.74\left(\frac{g}{U\omega}\right)^4} \tag{4.6}$$

where:

$S(\omega)$ = spectral energy density (ft^2 sec)
ω = wave frequency (rad/sec)
g = gravitational acceleration
U = wind velocity at height of 19.5 meters above the free surface

Figure 4.5 shows the Pierson-Moskowitz sea spectrum for wind speeds of 15, 20, 25, and 30 knots. As the wind speed increases, the amplitude of the wave spectra becomes significantly higher and the peak frequency of the spectrum decreases and approaches the natural frequency of the towing system.

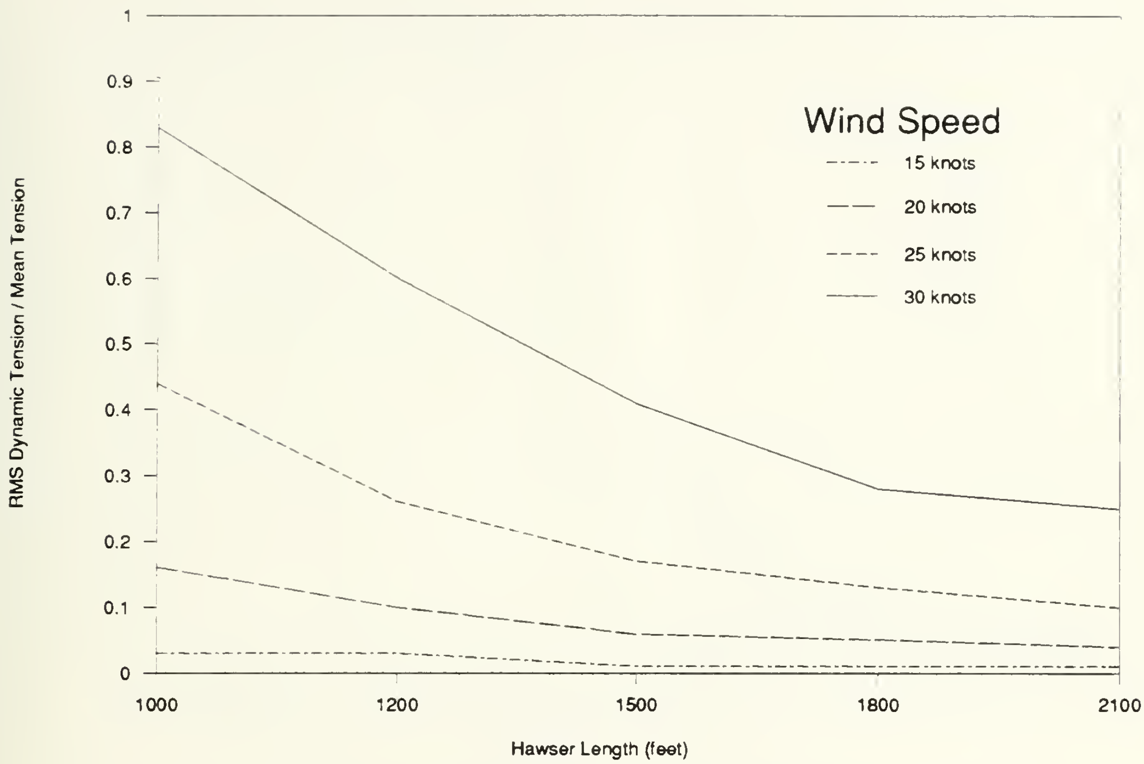

Figure 4.4 Influence of Sea Conditions (LHA at 40 kips mean tension)

The natural frequency (f_n) of a towing system can be expressed, to a first order approximation, as a function of towline stiffness (k_{eq}) and the towing system mass, including hydrodynamic added mass, (M) as follows:

$$f_n = \sqrt{\frac{k_{eq}}{M}} \tag{4.7}$$

The natural frequencies for towing systems are typically in the range 0.05 to 0.50 rad/sec which are lower than the spectral peak frequencies. Therefore, for a given static tension, decreasing the length of cable causes the cable stiffness to increase and results in a shifting of the natural frequency to higher values and moving it closer to the spectral peak. Large dynamic tensions result when the natural frequency enters the range of significant wave energy.

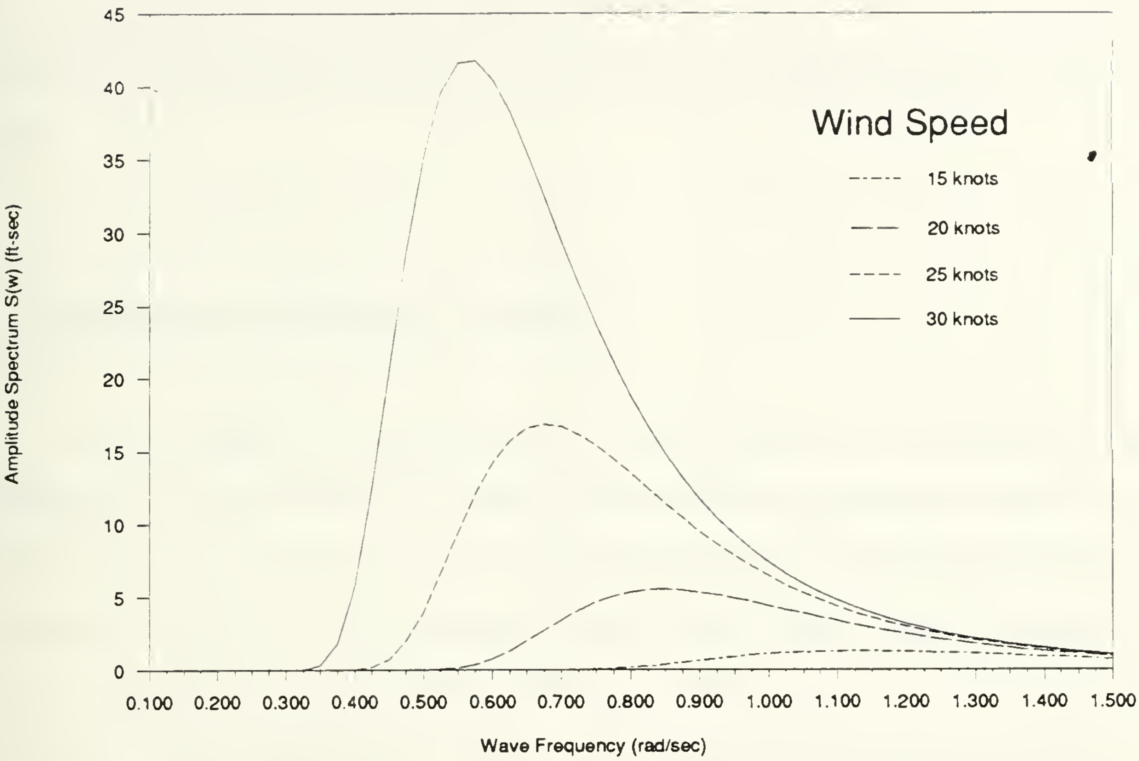

Figure 4.5 Pierson-Moskowitz Sea Spectrum

As related to sea conditions, the magnitude of the RMS dynamic tension is influenced by the length of towing cable, especially at shorter lengths. This is because the decreased sag in the catenary results in an increase in the cable stiffness which, in turn, increases the dynamic tensions. As the length of the cable is increased, the influence of the wind diminishes rapidly as more cable sag is present to dampen and absorb the effects of the end point extension.

The dynamic tension at 15 knots wind speed differed from the mean tension by, at most, four percent for all conditions investigated. This is considered to be too small for discrimination from "noise" in the mean tension levels during an experiment. Therefore, the lower threshold for the actual wind speed (ship's speed plus relative wind speed) for the

experiment should be greater than 15 knots. It is highly desirable to have wind speeds higher than 20 knots to develop measurable differences between the dynamic and mean static tensions.

4.5 Influence of Mean Tension

As shown in figure 4.6, increasing the mean cable tension results in an increase in the magnitude of the dynamic tension. Changes in mean tension are generally developed by a change in the span between two ships. As the hawser straightens out, the sag of the catenary is reduced. The effect of this is to reduce the cable's ability to absorb further extensions without a significant increase in the dynamic tension. This can also be seen by the hawser's static tension versus elongation curve (figure 4.3). Increasing the mean tension results in a larger local slope on the curve and so larger dynamic tensions result from the same amount of elongation. To achieve distinct and measurable dynamic tensions during the experiment, shorter scopes of hawser should be used when lower values of mean tension are present.

4.6 Influence of Size of Tow

Up to now, only discrete mean tensions, chosen "a priori," have been investigated. However, this procedure cannot be used directly to investigate the influence of the size of tow on the developed dynamic tensions. This is because each vessel will have a different mean tension value depending upon its unique hull form and characteristics. Therefore, an estimated value of the mean static for each ship must be computed before comparison between different sized ships can be accomplished.

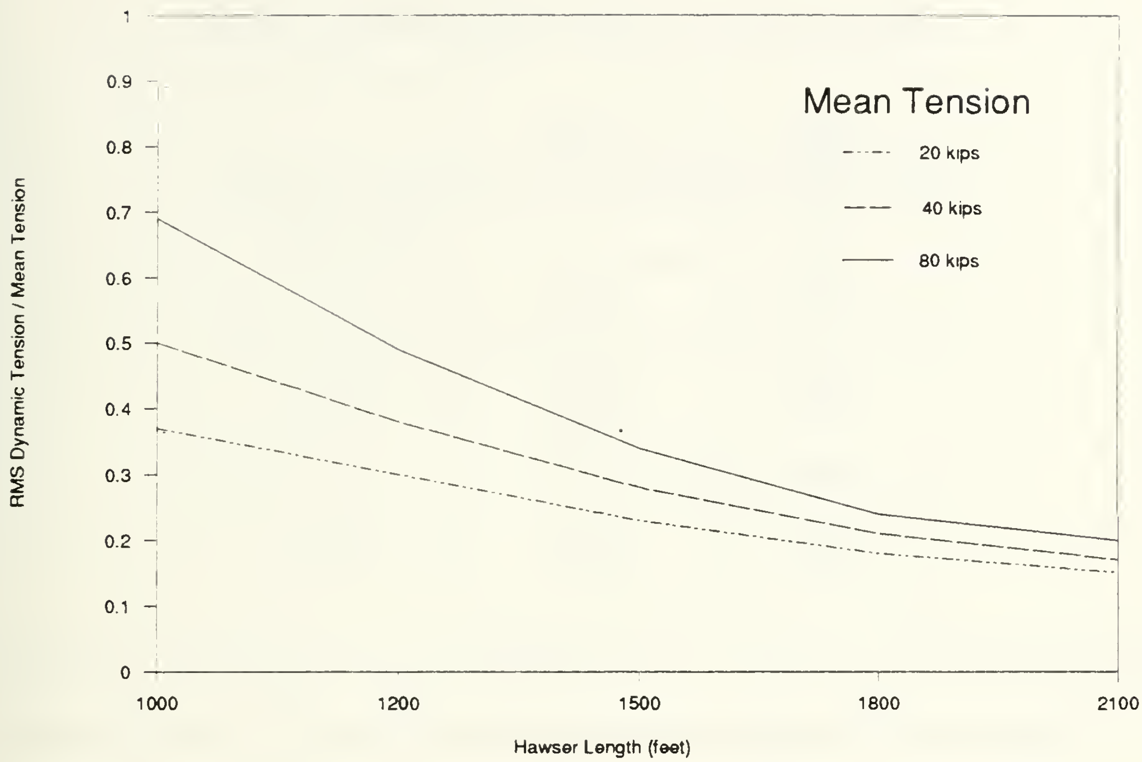

Figure 4.6 Influence of Mean Tension (LHA at 25 knots wind)

The mean static tension ($\overline{T}$) in the towing hawser can be estimated using the procedures outlined in U.S. Navy Towing Manual (1988). This procedure accounts for sea state, hull, propeller, and wind resistances. The mean tensions developed with the ARS 50 towing both the FFG 1 and LHA 1 were computed for four different wind conditions based on a ship's speed of three knots and heading seas are shown in table 4.3.

Values for the developed dynamic tension have been plotted in figure 4.7 which shows that the relative magnitude of the dynamic tension is always greater with the larger sized ship. This is because the predominant factor in the towline tension is caused by the movement of the ships and so the vessel with the greater displacement will develop a larger inertia

Table 4.3 Expected Mean Tensions at 3 knots, heading seas

	FFG 1	LHA 1
wind speed	$\overline{T}$	$\overline{T}$
15 knots	12 kips	31 kips
20 knots	14 kips	40 kips
25 knots	17 kips	55 kips
30 knots	23 kips	80 kips

while towing. The distinction in size diminishes at lower wind speeds and longer lengths of towing hawser because the hawser is able to absorb more extension with little change in dynamic tension. The phase difference between the surge motions of the tow and tow will then be the prime factor in determining the magnitude of the developed dynamic tensions.

Figure 4.7 shows that there is a trade off between wind speed and the size of tow. At higher wind speeds (25 knots) the importance of vessel size diminishes as measurable dynamic tensions can be obtained from either size vessel. However, at lower wind speeds the length of the towing hawser becomes more significant. At 15 knots of wind, the magnitude of the dynamic tension developed by either size vessel is so small that it is doubtful that meaningful measurements could be recorded. Based on these observations, the experiment should be conducted with a larger sized vessel because the developed RMS dynamic tension was always greater than the smaller vessel. To achieve measurable dynamic tensions with smaller sized tows, it is recommended to tow at shorter hawser lengths.

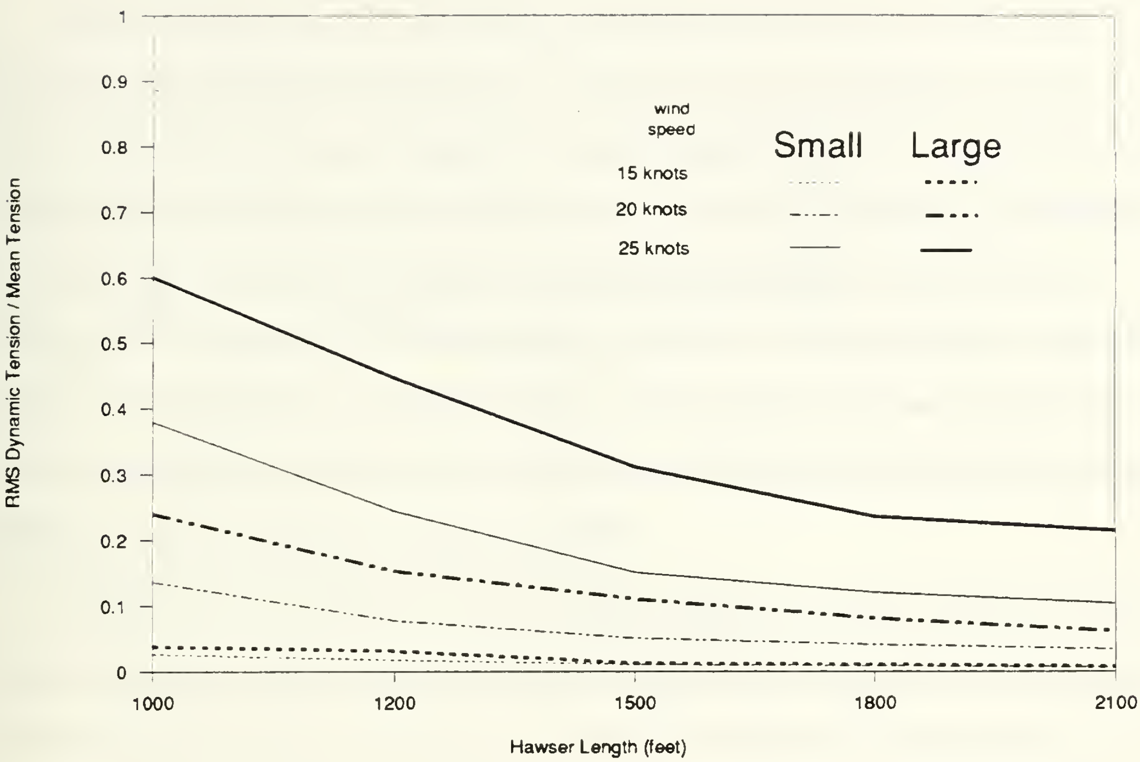

Figure 4.7 Influence of Size of Tow (25 knots wind)

4.7 Summary

From the above analyses, it is obvious that all four factors investigated (sea conditions, hawser length, mean tension, and size of tow) are interrelated and affect the dynamic tensions developed while towing to different extents. Since the purpose of this validation experiment is to compare measured tensions to analytical predictions, it is necessary that a wide range in dynamic tensions be developed in the hawser. This will allow greater discrimination between the different cases and help to ensure that meaningful results are obtained.

The most important factor influencing the magnitude of the dynamic tension is the mean tension as it defines the location on the static tension versus elongation curve. The local sea conditions and hawser length also contribute significantly to the development of dynamic tensions. The local sea conditions appear to have a greater influence the development of dynamic tensions than the effect of changing hawser length. This is expected because tension is a function of cable elongation (equation 1.6) and sea conditions cause the ships to move which results in cable elongations. Based on these analyses, the experiment must be conducted in a region with local wind speeds of 18 knots or more in order to develop needed measurable differences in dynamic tensions.

In addition to sea conditions, dynamic tensions appear to be highly sensitive to hawser length. Increasing the length of the towing hawser significantly reduces the dynamic tension as the cable becomes "softer." In all cases investigated, shorter hawser lengths provided a wider range of dynamic tensions. Therefore, shorter scopes of towing hawser should be used in the experiment when lower values of mean tension are anticipated and when smaller sized tows are used.

Chapter Five

Equipment Selection

5.1 Measurement Specifications

The initial step in the selection of instrumentation was to define a set of measurement specifications. The goal was to specify the required measurement tolerances for each instrument that would provide sufficient resolution for proper analysis. This was based both on an analysis of previous test plans, Milgram (1986), and the analytical model predictions obtained during the sensitivity analysis (chapter 4). A summary of the measurement specifications for this experiment is provided in Table 5.1. In addition to specifying a frequency and anticipated range of values for each measured parameter, a required precision has been expressed in terms of an absolute error. All dynamic measurements include a relative error which is based on the overall system error, not just the individual sensor itself.

5.2 Provision of Instrumentation

To accomplish this experiment, complex and highly specialized instrumentation is needed. A primary consideration in the selection of instrumentation was the desire to allo-

cate responsibility for all data signals to a single organization. This would not only minimize confusion and misunderstanding of individual responsibilities but also, hopefully, reduce field problems by allowing all instrumentation to be assembled and tested in a single laboratory prior to installation. Other significant factors used in the selection of equipment were compactness, reliability, accuracy, self sufficiency, and having sufficient resolution to provide statistically significant data even when sea conditions are relatively calm. Every attempt to minimize interference with or dependence upon installed shipboard systems was made. Several possible methods of obtaining the required instrumentation were investigated; provision by a U.S. Navy laboratory, assembling it using resources available at MIT, or subcontracting to a commercial company.

Several Navy laboratories are experienced in measuring ship motions and environmental conditions. Both the David Taylor Research Center (DTRC) and the Naval Civil Engineering Laboratory (NCEL) in Port Hueneme, California offered assistance. However, since they both could only provide a limited amount of the required instrumentation, the use of a U.S. Navy laboratory was found to be infeasible for this experiment. The cost and lead time of acquiring the highly specialized equipment made it uneconomically feasible to attempt outfitting directly at MIT. Therefore, the most economical alternative was found to subcontract out to a commercial company. Table 5.2 provides a listing of all instrumentation selected for the experiment.

5.3 The Tug and Tow

The selection of naval ships for use in the experiment was based primarily on availability of resources rather than meeting any specific design specifications. However, a conscious

Table 5.1 Measurement Specifications

Parameter	Frequency (Hz)	Range	Absolute Error	Relative Error
Wind Speed Direction	 0 - 0.2 0 - 0.2	 0 - 50 knots 0 - 360 deg.	 1.0 knot 1.0 deg.	 - -
Speed	0 - 0.2	0 - 15 knots	0.1 knot	-
Heading	0 - 0.2	0 - 360 deg	1.0 deg.	-
Separation	0 - 0.2	300 - 2000 ft	4.0 ft	-
Hawser angle horizontal vertical	 0 - 0.2 0 - 0.2	 ± 45 deg. 0 - 80 deg.	 1.0 deg 1.0 deg	 - -
Tension	0.015 - 2.0	2 - 100 kips	200 lbs	-
Surge	0.015 - 0.3	± 25 ft	0.1 ft	2%
Sway	0.015 - 0.3	± 25 ft	0.1 ft	2%
Heave	0.015 - 0.3	± 25 ft	0.1 ft	2%
Roll	0.015 - 0.3	± 25 deg	0.5 deg.	3%
Pitch	0.015 - 0.3	± 10 deg	0.2 deg.	3%
Yaw	0.015 - 0.3	± 10 deg	0.2 deg.	3%
Wave Height	0.03 - 0.3	± 25 ft	0.1 ft	2%

effort was made to find a "larger" sized vessel to help in obtaining a wider range of dynamic tensions as shown in chapter 4. The two naval vessels selected to participate in this experiment are the USS SALVOR (ARS 52) and the ex-USS HECTOR (AR 7). The characteristics of these ships are shown in Table 5.3.

The USS SALVOR (ARS 52) is a "Safeguard" Class Salvage ship. Commissioned on 14 June 1986, the SALVOR is a member of the newest salvage ship in the U.S. Navy inventory. She is powered by four Caterpillar D-399 diesel engines which produce a total of 4200 SHP. The SALVOR has an Almond A. Johnson Series 322 automatic towing machine which

Table 5.2 Summary of Instrumentation

Item	Manufacturer	Model Number
Tension	StrainSert Tension Link StrainSert Clevis Pin	STL-80 (SS) SPA 180-1.5 SGK
Wind	Skyvane Wind Sensor	2101
Wave Height	TSK wave height meter	---
Speed	Northstar LORAN C	5000
Heading	Cetrek Electronic Compass	930-550
Range	Dr. Rigel Laser Range Finder	LR90-80
Signal conditioners	VISHAY amplifier	2310
Motions	Humphrey vertical gyro Glennite accelerometers	VG 34-0301-1 LA 820201

holds 3000 feet of 2.25 inch wire towing hawser in addition to a series 400 traction winch for 14 inch fiber rope hawsers. The SALVOR is capable of producing 138,000 pounds of bollard pull thrust.

The ex-USS HECTOR (AR 7) is a "Vulcan" Class Repair ship commissioned on 7 February 1944. She was recently decommissioned from active duty in the U.S. Navy and is currently moored at the Naval Station Pearl Harbor, Hawaii awaiting transfer to the Pakistani Navy. The HECTOR is currently in the custody of the Inactive Ship Maintenance Facility, Pearl Harbor, Hawaii. Permission from the office of the Chief of Naval Operations (CNO) has been obtained to use the vessel in this towing experiment prior to the transfer of ownership.

Table 5.3 Gross Characteristics of Test Platforms

	TUG	TOW
Ship	ARS 52	AR 7
Length (ft)	255	520
Beam (ft)	52	73
Draft (ft)	15.5	15.5
Displacement (Ltons)	2,850	10,130

Chapter Six

Analytical Predictions

6.1 Background

Since towing conditions must be set so the probability of towline failure is very small, the U.S. Navy Towing Manual (1988) estimates extreme tensions based on a probability of 0.1% of being exceeded in one day of towing. Since those extreme tensions occur, on the average, only once in 1000 days of towing, they cannot be directly measured in a practical experiment. Instead, the theory can be used to determine the most probable extreme tension to be encountered during a discrete time interval, such as one hour, and can provide a complete probability distribution function for the extreme tension during that time interval. Agreement between measurement and theory would provide high confidence for application of the theory to the more rare extremes of interest in actual towing operations.

Although final analysis and comparison of analytical tension predictions to actual measurements can only be done upon completion of the experiment, analytical predictions must be available prior to the experiment. This will provide a means of on-scene evaluation of the data as it is being recorded which will help to identify errors in the measurement procedures.

Additionally, these predictions can be used to preselect conditions for conducting the experiment such that a higher range of dynamic tensions can be anticipated. During the post-voyage data analysis, the exact conditions that were measured can be individually input into the different analytical models and the results compared with actual measurements. In this manner, each phase of the model can be individually verified or modified as necessary to achieve good correlation between the analytical predictions and actual measurements.

6.2 Methodology

To obtain a set of predictions for the experiment, the analytical method outlined in section 1.3 was used. Ship motion responses to different sea conditions were computed using seakeeping theory based on the proposed towline configuration (table 6.1). The influence of towline tension on these motions was then accounted for using the method of equivalent linearization. The resulting ship motions were then coupled with the Numerical Towline Model to evaluate dynamic tensions. To account for the unknowns during actual measurement during the experiment, three speeds, four relative wave angles, four different mean tensions and five different hawser lengths were modeled. Since it is highly unlikely that an extreme tension will be encountered during the short duration of testing, the analytical predictions are based on the RMS values of tension which were computed from the zeroeth moment of the tension spectrum.

The resulting predictions comprise a large set of data which is presented in Appendix B. To simplify the presentation, the data is displayed in a series of 16 different curves (figures B.1 through B.16). An estimate for the RMS value of tension for a specific condition can be thus be obtained by interpolating between the different graphs.

Table 6.1 Characteristics of Towline in Validation Experiment

	WIRE	CHAIN
Type	6x37 IWRC (EIPS)	anchor (grade 1)
Length	2100 ft	bridle: 2 x 135 ft pendant: 180 ft
Size	2.25 in	2.75 in
Elastic Modulus	12.6×10^6 psi	30×10^6 psi
Weight	8.31 lbs/ft	74 lbs/ft
Breaking Strength	444,600 lbs	413,000 lbs

6.3 Estimation of Mean Static Tension

Since the analytical model predictions are computed based on mean tension values chosen "a priori," a knowledge of the mean tension is required in order to use them. During the actual experiment this will be readily available from the installed tensiometer. To estimate the expected mean static tension for the HECTOR before the experiment, the method described in the U.S. Navy Towing Manual (1988) can be used. Figure 6.1 shows estimates for the mean static tension for the HECTOR at different wind and towing speeds in relation to the available pulling power curve of the SALVOR. The available pulling power represents the difference between the total thrust that the ship is able to generate at a given speed and the amount of thrust that is expended in propelling the tug itself at that speed. Therefore, the intersection of these two curves represents a peak operating condition in which the engines are operating at full capacity. Using this notion, we can define a set of maximum operating conditions as a function of wind speed. The results are shown in table 6.2.

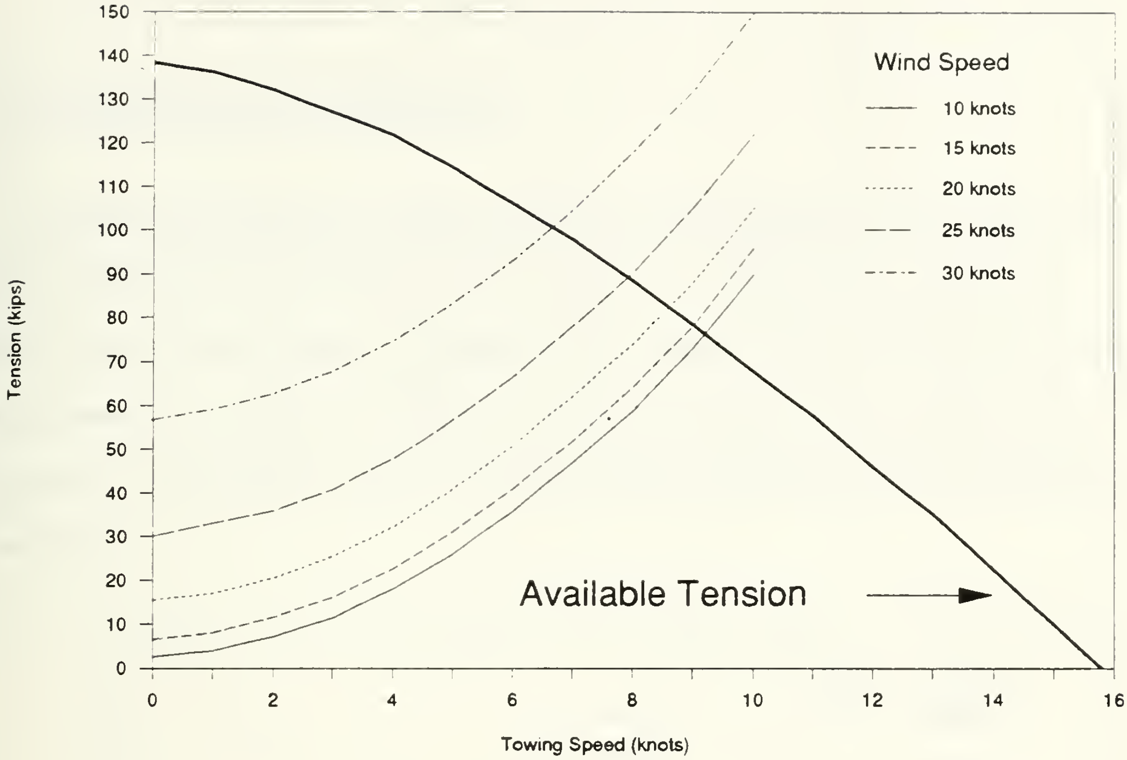

Figure 6.1 Estimated Mean Tension and Available Pulling Power for the SALVOR towing the HECTOR

Table 6.2 Maximum Operating Conditions for the experiment (1000 ft hawser)

Wind Speed (knots)	Maximum Towing Speed (knots)	Mean Static Tension (kips)
15	9.0	78
20	8.5	82
25	7.8	90
30	6.6	100

6.4 Analytical Predictions

The analytical predictions of RMS towline tension appear to be consistent with relationships identified in the sensitivity analysis (chapter 4); shorter hawser lengths show greater dynamic tension extremes, especially at higher values of mean tension and that wind speeds greater than 15 knots are required in order to have measurable dynamic tensions developed. This can be seen in figure 6.2, which contains plotted data from the tables B.1 through B.12.

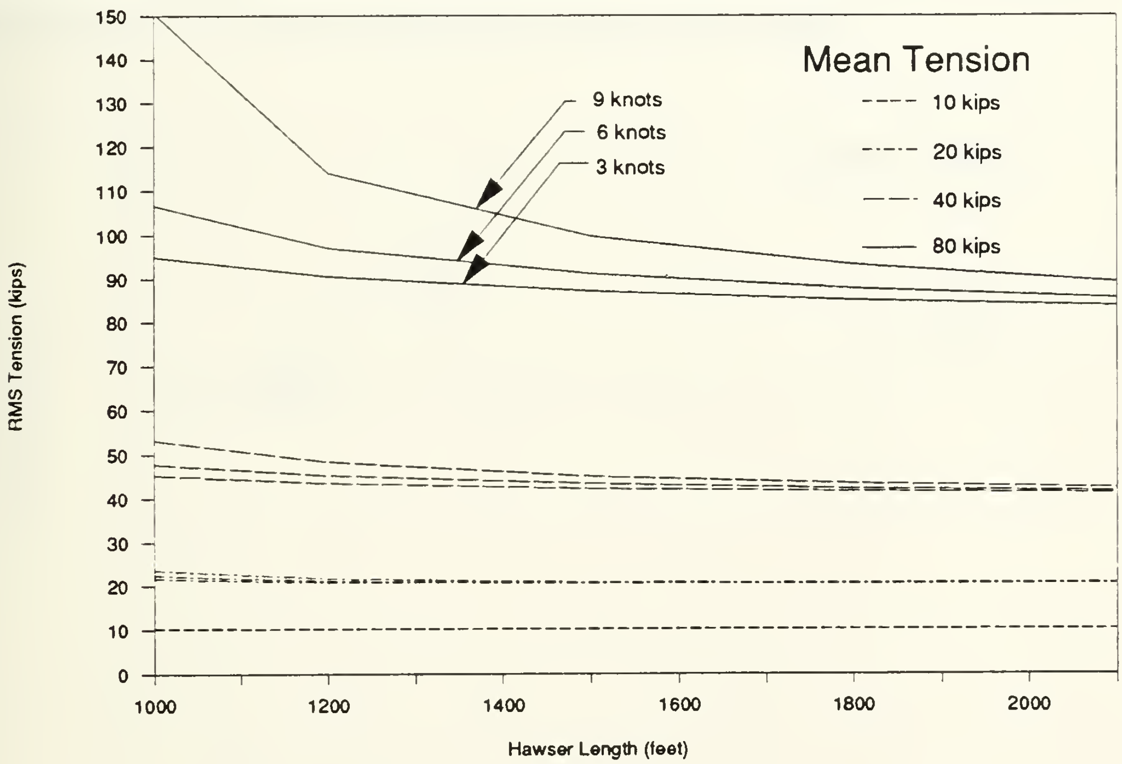

Figure 6.2 ARS 52 towing AR 7 at relative wave angle 000, wind speed 20 knots

Comparison of dynamic tensions developed while towing at different wave angles, as shown in figures 6.2 and 6.3, reveals that the magnitude of the developed dynamic tension is highly dependent upon the relative wave angle, especially at higher values of mean tension. Heretofore, only heading seas (relative wave angle of 180 degrees) were investigated because heading seas are the most common encountered while towing at higher sea states, since, as the sea state increases, the tug and the tow will generally be forced to head into the seas. For a given mean tension, the largest dynamic tensions are developed in following seas (relative wave angle equal to zero degrees) and the magnitude of the dynamic tensions decreases dramatically as the relative wave angle increases. This is because in following seas, the frequency spectrum of the seas tunes with the natural frequency of the towing system which results in greater ship motions and therefore larger dynamic tensions.

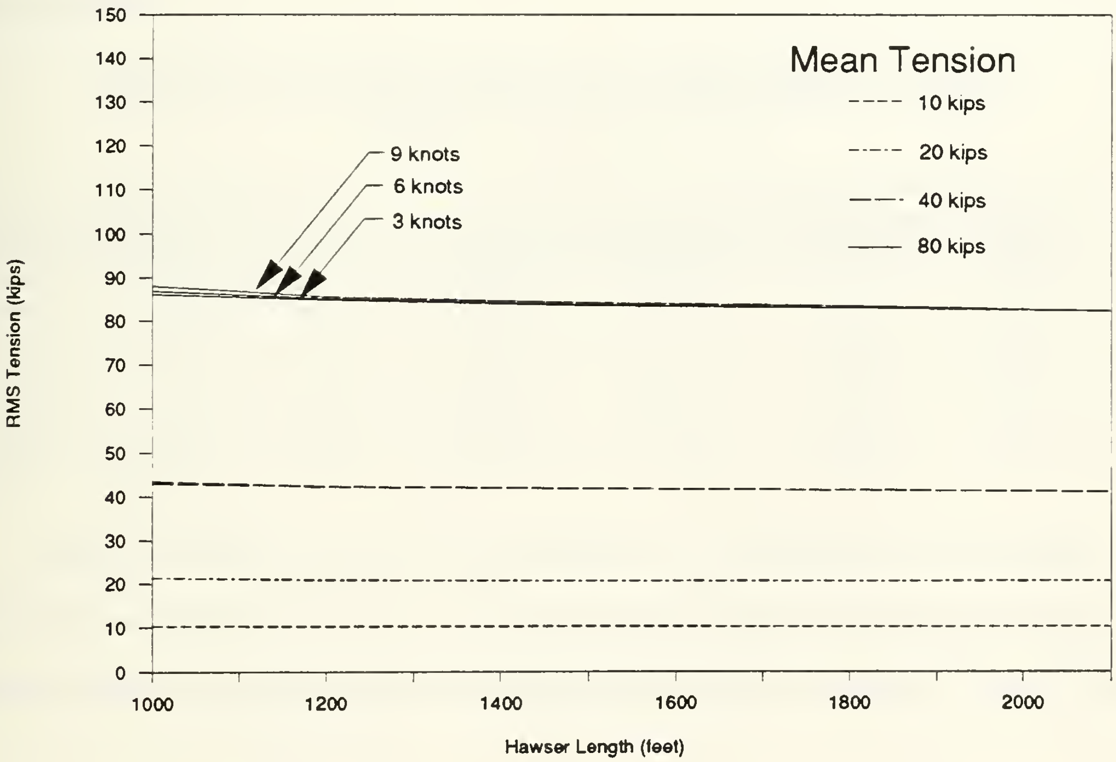

Figure 6.3 ARS 52 towing AR 7 at relative wave angle 180, wind speed 20 knots

In the sensitivity analysis we found that wind speeds greater than 15 knots were needed when towing at three knots in order to have measurable dynamic tensions developed. This corresponds to a significant wave height of 4 feet. Based on the historical mean wind speeds off Oahu, figure 2.1 the average mean wind speed is approximately 13 knots. However, when more specific statistical wave height information is investigated (table 6.3), we see that the there is a 90% probability that the wave height will be 6.6 feet or greater. This corresponds to a sea state of five that would typically have a wind speed of 19 knots. The reason for the wave heights to be larger than typical predictions can be attributed to the fact that Hawaii is an island and there are very long fetch lengths. Since the effect of sea conditions on the motions of the ship is largely a function of wave height, and not wind speed, this further emphasizes the conclusion in chapter two that Hawaii is the optimum location to conduct the experiment.

Table 6.3 Statistical Wave Height Data near Oahu, Hawaii (April 1986)
(Mariners Weather Log, Vol 30)

buoy	3.3-4.9 ft	6.6-8.2 ft	9.8-11.5 ft	13.1-14.8 ft	Maximum	Mean
51002	9.7 %	41.7 %	46.3 %	2.2 %	13.1 ft	8.5 ft
51003	9.3 %	64.0%	20.4 %	6.1 %	18.0 ft	8.2 ft
51004	3.1 %	50.4 %	40.6 %	5.6 %	14.8 ft	8.9 ft
51005	10.3 %	51.4 %	30.3 %	7.8 %	18.0 ft	8.5 ft

Figures 6.2 and 6.3 show that towing speed has very little influence on the dynamic tensions below 20 kips mean tension. This indicates that the primary factor developing the tension is due to seakeeping response of the ships rather than due to additional engine thrust.

During the experiment, when the actual wind conditions and static mean tension will be known, these predictions can be very useful in selecting the hawser scope, speed, and course to tow on during each data collection period to have a greater certainty of experiencing larger and more measurable dynamic tensions.

Chapter Seven

Conclusions

7.1 Summary

This study has been a practical extension of previous work done at MIT on the dynamics of tension in towing hawsers. A sensitivity analysis has been conducted to investigate the relative importance of various parameters (hawser length, wind speed, mean tension, and size of tow) on the magnitude of the resulting dynamic tensions. Although all lengths are acceptable for measurement purposes, shorter hawser lengths provide larger range in dynamic tensions. A lower bound on wind speed has been established at 18 knots when towing at three knots. Based on a parametric study and analysis of coastal weather patterns, Hawaii has been selected as the best test location. Equipment selection was based on a set of developed measurement specifications.

As a result of this work, a validation experiment has been planned, organized, and scheduled. The Navy has designated two ships, the USS SALVOR (ARS 52) and the ex-USS HECTOR (AR 7), to be test platforms for the validation experiment. The experiment is scheduled for early May off the coast of Oahu, Hawaii. All equipment needed for this

experiment has been assembled. tested, and is ready for shipment. A series of analytical predictions, based on the RMS values of tension, have been developed (Appendix B) for on-scene data analysis and to assist in the selection of the best course and speed combination to obtain measurable dynamic tensions during the experiment. Appendix C provides the test plan that has been developed and issued to all involved personnel specifying the procedures and support requirements for the experiment. Unfortunately, the late date of this experiment precludes the inclusion of any post-voyage analysis with this study. However, upon completion of the experiment, a full report will be issued describing the results.

7.2 Further Studies

This work represents the first step in confirming the applicability of the MIT analytical model used to predict dynamic towline tension extremes. Post-voyage analysis of data collected during the towing experiment will hopefully verify the approach taken or indicate weaknesses which can then be modified using the measured results as a benchmark to achieve better correlation.

The experiment has been planned to measure a wide variety of parameters to generate a wealth of raw data for further analysis. Although the main purpose is to conduct seakeeping tests to confirm the influence of ship motions, especially surge, on cable extension and the resulting dynamic tension, four other tests are planned in conjunction with this; towing machine dynamic response test, fiber rope test, elastic wave test, and a transient response test.

The analytical models used to predict extreme tensions are based on ship motions as influenced by linear towline forces using the method of equivalent linearization. However, if

the actual non-linear forces and moments on the ship due to the towline could be predicted, the accuracy of the model would improve. Comparison of measured values to the linear approximations could provide an insight into predicting these non-linear forces. Additionally, the influence of the second order, slowly-varying component of dynamic tension (T_2) has been neglected in all analyses to date. It is hoped that by measuring the time history change in hawser horizontal angle, a relationship can be found to account for this in future work.

This study has only investigated wire rope towlines. Since fiber ropes are lighter and softer, their tension verses extension behavior should be much less non-linear than the wire and so easier to predict. An analytical model has been developed to predict the tension extremes in fiber towing hawsers (Milgram, 1988). All measurement procedures and instruments used for the wire rope analysis are suitable for a similar analysis of fiber cables. The last day of the experiment is now planned to include measurement while towing with a fiber towing hawser. Hopefully, data collected during this experiment can also validate that analytical model.

References

Anagnostou, G. (1987). Extreme tension in a ship's towline. Master's thesis, Massachusetts Institute of Technology, Department of Ocean Engineering, Cambridge, MA.

Bhattacharyya, R. (1978). Dynamics of marine vechiles. New York: Wiley.

Campman, C. R., & Debord, F. W. (1985). Tow monitoring system design for the real world (OTC 5045). Paper presented at the 17th Annual Offshore Technology Conference, Houston.

Comstock, J. P. (Ed.). (1967). Principles of naval architecture (rev. ed.). New York: The Society of Naval Architects and Marine Engineers.

DeBord, F. Jr., Purl, J., Mlady, J., Wisch, D., & Zahn, P. (1987). Measurement of full-scale barge motions and comparision with model test and mathematical predictions. SNAME Transactions, 95, 319-335.

Durgin, F. H. (1975). Use of anemometers in on-site studies of buildings and structures and in particular the Bendix Frieze anemometers. Unpublished manuscript, Massachusetts Institute of Technology, Wright Brothers Wind Tunnel, Cambridge, MA.

Frimm, F. D. C. (1987). Non-linear extreme tension statistics of towing hawsers. Doctoral dissertation, Massachusetts Institute of Technology, Department of Ocean Engineering, Cambridge, MA.

Frimm, F. D. C. and Milgram, J. H. (1986). Analysis of full-scale towing experiments. Unpublished document.

Kim, M. H. & Yue, D.K.P. (1989). Slowly-varying wave drift forces in short-crested irregular waves. Applied Ocean Research, 11(1), 2-18.

Loukakis, T. (1970). Computer-aided prediction of seakeeping performance in ship design (Technical Report). Cambridge, MA: Massachusetts Institute of Technology.

Milgram, J., Triantafyllou, M., Frimm, F., Anagnostou, G. (1988). Seakeeping and extreme tensions in offshore towing. Paper presented at the Annual Meeting of the Society of Naval Architects and Marine Engineers, New York.

Milgram, J. H. (1986). Plans and specifications for towing test measurements. Unpublished document.

Naval Sea Systems Command. (1988). U.S. Navy Towing Manual (rev. 1) (SL740-AA-MAN-010). Washington, DC.

Salvesen, N., Tuck, E. O., & Faltinsen, O. (1970). Ship motions and sea loads. SNAME Transactions, 78.

Sellars, F. H. (1967). The dynamic calibration of shipborne wave gages (Report No. 67-11). Cambridge, MA: Massachusetts Institute of Technology.

Triantafyllou, M. S. (1987). Nonlinear dynamics of marine cables and hawsers (Technical Report). Cambridge, MA: Massachusetts Institute of Technology.

Appendix A

Salvage Ships of the U.S. Navy

The following is a list of Salvage Ships on active duty in the U.S. Navy which could be used for the towing experiment.

POWHATAN Class Fleet Tugs

USNS POWHATAN (T-ATF 166)
USNS NARRANGANSETT (T-ATF 167)
USNS CATAWBA (T-ATF 168)
USNS NAVAJO (T-ATF 169)
USNS MOHAWK (T-ATF 170)
USNS SIOUX (T-ATF 171)
USNS APACHE (T-ATF 172)

SAFEGUARD Class Salvage Ships

USS SAFEGUARD (ARS 50)
USS GRASP (ARS 51)
USS SALVOR (ARS 52)
USS GRAPPLE (ARS 53)

DIVER/BOLSTER Class Salvage Ships

USS PRESERVER (ARS 8)
USS BOLSTER (ARS 38)
USS CONSERVER (ARS 39)
USS HOIST (ARS 40)
USS OPPORTUNE (ARS 41)
USS RECLAIMER (ARS 42)
USS RECOVERY (ARS 43)

EDENTON Class Salvage and Rescue Ships

USS EDENTON (ATS 1)
USS BEAUFORT (ATS 2)
USS BRUNSWICK (ATS 3)

ABNAKI Class Fleet Tugs

USS PAIUTE (ATF 159)
USS PAPAGO (ATF 160)

PIGEON Class Submarine Rescue Ships

USS PIGEON (ASR 21)
USS ORTOLAN (ASR 22)

CHANTICEER Class Submarine Rescue Ships

USS FLORIKAN (ASR 9)
USS KITTIWAKE (ASR 13)
USS PETREL (ASR 14)
USS SUNBIRD (ASR 15)

Appendix B

Analytical Predictions

Table B.1 RMS Towline Tension (kips) for ARS 52 towing AR 7 at 3 knots with 10 kips mean tension

Wave Angle	Wind Speed	1000 ft	1200 ft	1500 ft	1800 ft	2100 ft
000	15	10.1	10.1	10.1	10.1	10.0
000	20	10.3	10.2	10.2	10.1	10.1
000	25	10.6	10.5	10.4	10.3	10.3
000	30	11.0	10.8	10.7	10.5	10.4
060	15	10.2	10.2	10.2	10.1	10.1
060	20	10.5	10.5	10.5	10.3	10.3
060	25	10.8	10.7	10.7	10.5	10.4
060	30	11.1	11.0	11.0	10.6	10.5
120	15	10.3	10.2	10.3	10.1	10.0
120	20	10.7	10.7	10.7	10.4	10.3
120	25	11.2	11.1	11.0	10.7	10.7
120	30	11.4	11.4	11.3	10.9	10.9
180	15	10.1	10.1	10.1	10.1	10.1
180	20	10.4	10.3	10.3	10.2	10.2
180	25	10.8	10.6	10.6	10.4	10.4
180	30	11.2	11.0	11.0	10.7	10.6

Table B.2 RMS Towline Tension (kips) for ARS 52 towing AR 7
at 6 knots with 10 kips mean tension

Wave Angle	Wind Speed	1000 ft	1200 ft	1500 ft	1800 ft	2100 ft
000	15	10.1	10.0	10.1	10.0	10.0
000	20	10.3	10.2	10.2	10.1	10.1
000	25	10.6	10.5	10.4	10.3	10.3
000	30	10.9	10.8	10.7	10.5	10.4
060	15	10.2	10.2	10.2	10.1	10.1
060	20	10.4	10.4	10.4	10.3	10.3
060	25	10.7	10.7	10.7	10.4	10.4
060	30	11.0	10.9	10.9	10.6	10.5
120	15	10.3	10.2	10.2	10.1	10.1
120	20	10.8	10.7	10.7	10.5	10.5
120	25	11.3	11.2	11.1	10.8	10.8
120	30	11.5	11.5	11.5	11.0	11.0
180	15	10.1	10.1	10.1	10.1	10.1
180	20	10.4	10.3	10.3	10.2	10.2
180	25	10.9	10.8	10.8	10.5	10.5
180	30	11.3	11.2	11.2	10.8	10.7

Table B.3 RMS Towline Tension (kips) for ARS 52 towing AR 7 at 9 knots with 10 kips mean tension

Wave Angle	Wind Speed	1000 ft	1200 ft	1500 ft	1800 ft	2100 ft
000	15	10.1	10.1	10.1	10.0	10.0
000	20	10.4	10.3	10.2	10.1	10.1
000	25	10.8	10.6	10.5	10.3	10.3
000	30	11.0	10.9	10.8	10.5	10.4
060	15	10.2	10.1	10.2	10.1	10.1
060	20	10.4	10.4	10.4	10.3	10.3
060	25	10.7	10.6	10.6	10.4	10.4
060	30	10.9	10.8	10.8	10.6	10.5
120	15	10.2	10.2	10.2	10.1	10.1
120	20	10.8	10.8	10.7	10.5	10.4
120	25	11.4	11.3	11.2	10.9	10.8
120	30	11.7	11.7	11.6	11.2	11.1
180	15	10.1	10.1	10.1	10.1	10.1
180	20	10.4	10.4	10.4	10.3	10.3
180	25	11.0	10.9	10.9	10.6	10.5
180	30	11.5	11.4	11.4	11.0	11.0

Table B.4 RMS Towline Tension (kips) for ARS 52 towing AR 7 at 3 knots with 20 kips mean tension

Wave Angle	Wind Speed	1000 ft	1200 ft	1500 ft	1800 ft	2100 ft
000	15	20.3	20.2	20.2	20.1	20.1
000	20	21.7	20.9	20.6	20.4	20.4
000	25	24.1	22.2	21.3	21.0	20.9
000	30	25.4	23.3	22.2	21.8	21.5
060	15	20.7	20.4	20.4	20.4	20.3
060	20	21.8	21.3	21.2	21.1	20.6
060	25	23.2	22.1	21.4	21.3	21.1
060	30	24.7	23.1	22.0	22.0	21.6
120	15	20.7	20.6	20.6	20.5	20.3
120	20	22.3	21.7	21.6	21.4	21.0
120	25	23.9	22.7	22.6	22.2	21.7
120	30	25.1	23.5	23.0	22.7	22.2
180	15	20.4	20.2	20.2	20.2	20.2
180	20	21.5	20.9	20.6	20.6	20.6
180	25	23.3	22.0	21.4	21.3	21.2
180	30	24.9	23.3	22.3	22.0	21.9

Table B.5 RMS Towline Tension (kips) for ARS 52 towing AR 7
at 6 knots with 20 kips mean tension

Wave Angle	Wind Speed	1000 ft	1200 ft	1500 ft	1800 ft	2100 ft
000	15	20.5	20.3	20.2	20.1	20.1
000	20	22.3	21.2	20.7	20.5	20.4
000	25	24.6	22.7	21.5	21.2	21.0
000	30	24.0	23.5	22.6	22.0	21.7
060	15	20.7	20.4	20.4	20.4	20.3
060	20	21.9	21.2	21.1	21.0	20.6
060	25	23.3	22.0	21.8	21.5	21.0
060	30	24.8	23.1	22.5	21.9	21.5
120	15	20.7	20.6	20.5	20.5	20.3
120	20	22.4	21.9	21.7	21.5	21.1
120	25	24.1	23.0	22.6	22.4	21.9
120	30	25.3	23.7	23.3	23.0	22.5
180	15	20.3	20.2	20.2	20.2	20.1
180	20	21.4	20.9	20.7	20.7	20.6
180	25	23.4	22.1	21.6	21.5	21.4
180	30	24.9	23.5	22.6	22.3	22.2

Table B.6 RMS Towline Tension (kips) for ARS 52 towing AR 7 at 9 knots with 20 kips mean tension

Wave Angle	Wind Speed	1000 ft	1200 ft	1500 ft	1800 ft	2100 ft
000	15	20.9	20.4	20.2	20.2	20.2
000	20	23.6	21.6	20.9	20.7	20.6
000	25	24.4	23.0	21.9	21.5	21.2
000	30	23.7	23.5	22.7	22.4	22.0
060	15	20.8	20.4	20.4	20.4	20.2
060	20	22.0	21.2	21.0	20.9	20.6
060	25	23.5	22.0	21.7	21.4	21.0
060	30	25.0	22.8	22.0	21.8	21.4
120	15	20.7	20.5	20.5	20.5	20.3
120	20	22.5	21.9	21.7	21.6	21.1
120	25	24.4	23.2	22.9	22.6	22.1
120	30	25.5	24.0	23.1	23.2	22.7
180	15	20.3	20.2	20.2	20.2	20.1
180	20	21.4	21.0	20.8	20.7	20.6
180	25	23.6	22.4	21.9	21.8	21.6
180	30	25.2	23.6	22.9	22.7	22.6

Table B.7 RMS Towline Tension (kips) for ARS 52 towing AR 7
at 3 knots with 40 kips mean tension

Wave Angle	Wind Speed	1000 ft	1200 ft	1500 ft	1800 ft	2100 ft
000	15	41.0	40.7	40.4	40.3	40.3
000	20	45.2	43.6	42.3	41.5	41.2
000	25	53.6	49.2	45.7	43.9	42.9
000	30	62.7	56.5	50.2	47.2	45.3
060	15	41.4	41.0	41.0	40.9	40.6
060	20	44.1	43.2	42.4	42.2	41.3
060	25	47.8	45.8	43.6	43.5	42.4
060	30	55.0	50.1	45.9	44.9	43.6
120	15	41.3	41.2	40.9	40.8	40.7
120	20	44.4	43.8	42.4	42.4	42.0
120	25	47.7	46.1	44.1	43.9	43.2
120	30	53.5	49.4	46.0	45.1	44.2
180	15	40.8	40.5	40.4	40.4	40.2
180	20	43.5	42.3	41.7	41.5	41.0
180	25	48.6	46.0	44.1	43.2	42.5
180	30	55.8	51.7	47.5	45.5	44.3

Table B.8 RMS Towline Tension (kips) for ARS 52 towing AR 7 at 6 knots with 40 kips mean tension

Wave Angle	Wind Speed	1000 ft	1200 ft	1500 ft	1800 ft	2100 ft
000	15	41.6	41.1	40.7	40.5	40.3
000	20	47.8	45.2	43.2	42.2	41.6
000	25	58.3	52.1	47.7	45.1	43.7
000	30	62.7	55.9	52.5	48.5	46.7
060	15	41.6	41.0	40.6	40.6	40.6
060	20	44.6	43.5	41.9	41.7	41.5
060	25	48.9	46.4	43.9	43.5	42.6
060	30	56.9	51.2	46.4	45.1	43.8
120	15	41.3	41.2	40.9	40.8	40.6
120	20	44.5	43.8	42.6	42.5	42.1
120	25	47.9	46.2	44.5	44.0	43.5
120	30	53.1	49.3	46.3	45.3	44.5
180	15	40.7	40.5	40.3	40.3	40.2
180	20	43.1	42.3	41.7	41.4	41.0
180	25	47.7	45.6	44.0	43.3	42.7
180	30	53.8	50.5	47.1	45.4	44.5

Table B.9 RMS Towline Tension (kips) for ARS 52 towing AR 7 at 9 knots with 40 kips mean tension

Wave Angle	Wind Speed	1000 ft	1200 ft	1500 ft	1800 ft	2100 ft
000	15	43.2	42.0	41.2	40.8	40.5
000	20	53.2	48.3	44.9	43.3	42.3
000	25	61.8	56.9	50.3	47.2	45.1
000	30	67.1	59.3	54.1	50.5	47.9
060	15	42.0	41.2	40.9	40.8	40.7
060	20	45.5	43.9	42.1	42.1	41.7
060	25	50.5	47.4	44.5	43.7	42.8
060	30	59.2	52.2	47.3	45.4	44.2
120	15	41.2	41.1	40.7	40.7	40.6
120	20	44.6	43.7	42.8	42.5	42.1
120	25	48.2	46.3	44.8	44.2	43.7
120	30	53.0	49.3	46.6	45.5	44.8
180	15	40.6	40.4	40.3	40.3	40.1
180	20	42.9	42.2	41.7	41.4	41.2
180	25	47.4	45.6	44.1	43.4	43.1
180	30	53.1	50.0	47.1	45.6	44.9

Table B.10 RMS Towline Tension (kips) for ARS 52 towing AR 7
at 3 knots with 80 kips mean tension

Wave Angle	Wind Speed	1000 ft	1200 ft	1500 ft	1800 ft	2100 ft
000	15	82.5	81.8	81.3	80.9	80.7
000	20	94.9	90.5	87.1	85.1	83.8
000	25	141.0	112.6	99.9	94.1	90.5
000	30	294.0	180.9	127.5	109.9	101.5
060	15	83.0	82.1	81.9	81.8	81.2
060	20	89.7	87.6	85.0	84.8	83.3
060	25	109.0	96.2	90.5	89.0	86.5
060	30	234.8	144.4	102.1	95.0	91.2
120	15	82.6	82.5	81.3	81.3	81.3
120	20	88.9	87.6	84.9	84.2	83.9
120	25	99.3	93.6	89.5	87.8	86.7
120	30	171.8	166.9	96.8	92.2	90.1
180	15	81.7	81.1	80.8	80.8	80.4
180	20	88.1	85.6	84.2	83.5	82.3
180	25	104.0	96.5	91.4	88.8	86.7
180	30	151.4	122.4	105.5	97.8	93.4

Table B.11 RMS Towline Tension (kips) for ARS 52 towing AR 7
at 6 knots with 80 kips mean tension

Wave Angle	Wind Speed	1000 ft	1200 ft	1500 ft	1800 ft	2100 ft
000	15	84.7	83.2	82.1	81.6	81.1
000	20	106.7	97.0	91.0	87.8	85.7
000	25	243.8	141.5	110.0	100.5	94.8
000	30	600.2	333.7	159.3	123.0	109.6
060	15	83.7	82.4	82.0	81.8	81.5
060	20	91.9	88.8	85.2	85.0	84.0
060	25	120.2	100.0	92.5	90.0	87.7
060	30	264.9	168.3	107.8	97.2	93.1
120	15	82.5	82.3	81.4	81.1	81.2
120	20	89.0	87.2	85.3	84.0	83.9
120	25	97.7	92.8	89.7	87.5	86.8
120	30	147.2	112.4	95.8	91.5	89.9
180	15	81.5	81.0	80.8	80.6	80.3
180	20	86.8	85.0	83.9	83.2	82.3
180	25	99.1	93.8	89.9	87.8	86.3
180	30	135.8	111.9	100.8	95.1	91.9

Table B.12 RMS Towline Tension (kips) for ARS 52 towing AR 7 at 9 knots with 80 kips mean tension

Wave Angle	Wind Speed	1000 ft	1200 ft	1500 ft	1800 ft	2100 ft
000	15	91.5	86.7	84.1	83.0	81.8
000	20	150.9	114.0	99.6	93.2	89.1
000	25	383.5	263.7	133.6	112.6	102.6
000	30	719.9	761.2	285.0	150.4	123.6
060	15	84.8	83.2	82.0	81.9	81.8
060	20	95.4	90.9	86.8	85.5	84.9
060	25	169.8	110.1	95.6	91.6	89.2
060	30	301.4	203.2	115.1	100.3	95.5
120	15	82.4	82.0	81.4	81.0	81.1
120	20	89.0	86.9	85.6	84.0	83.9
120	25	97.0	92.3	89.9	87.5	86.9
120	30	132.6	120.2	95.2	91.1	89.7
180	15	81.3	80.9	80.7	80.5	80.2
180	20	86.1	84.7	83.5	82.9	82.4
180	25	96.7	92.5	89.2	87.3	86.3
180	30	123.7	106.2	98.2	93.6	91.2

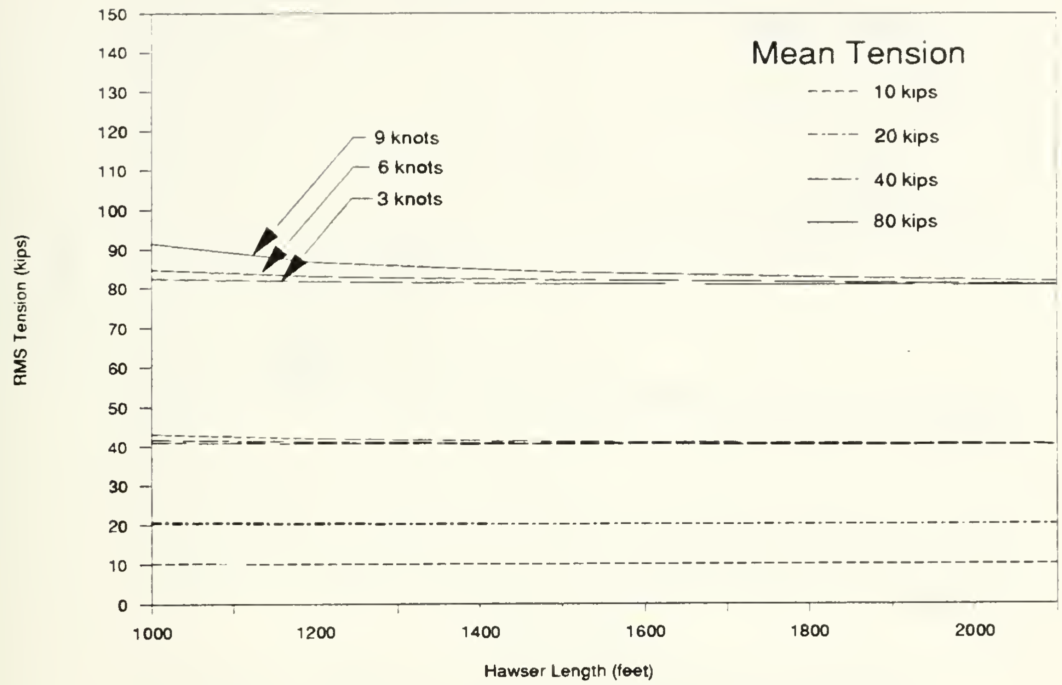

Figure B.1 ARS 52 towing AR 7 on 2.25 inch wire hawser
Relative Wave Angle 000, Wind Speed 15 knots

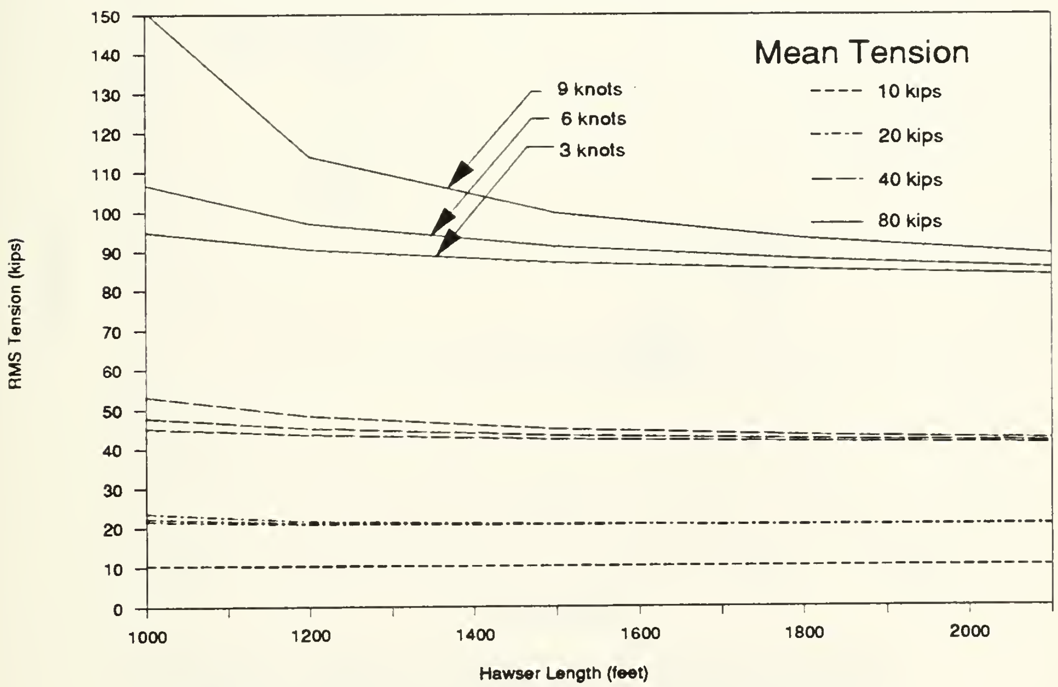

Figure B.2 ARS 52 towing AR 7 on 2.25 inch wire hawser
Relative Wave Angle 000, Wind Speed 20 knots

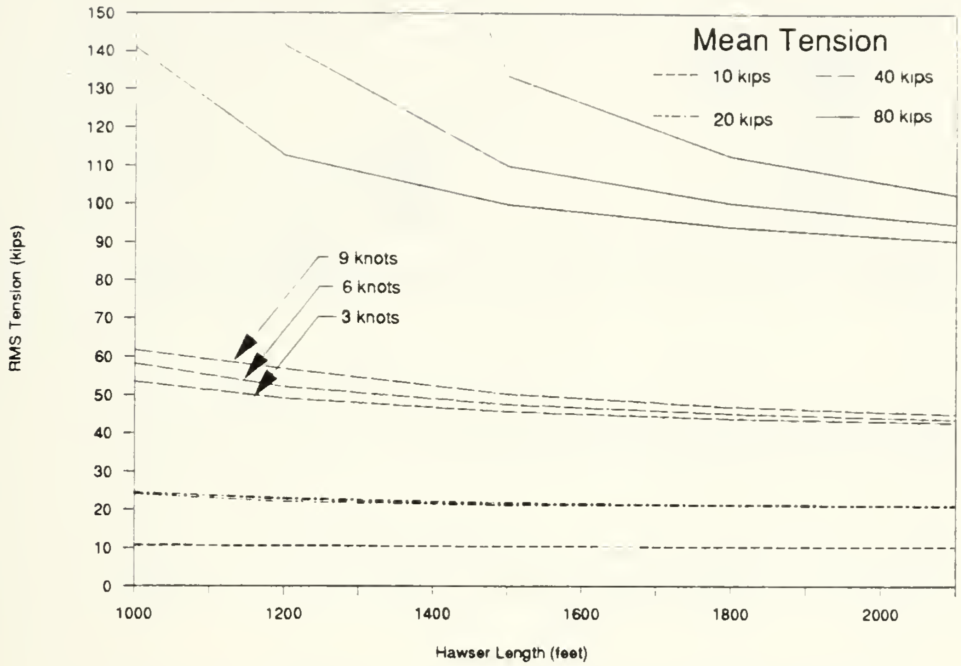

Figure B.3 ARS 52 towing AR 7 on 2.25 inch wire hawser
Relative Wave Angle 000, Wind Speed 25 knots

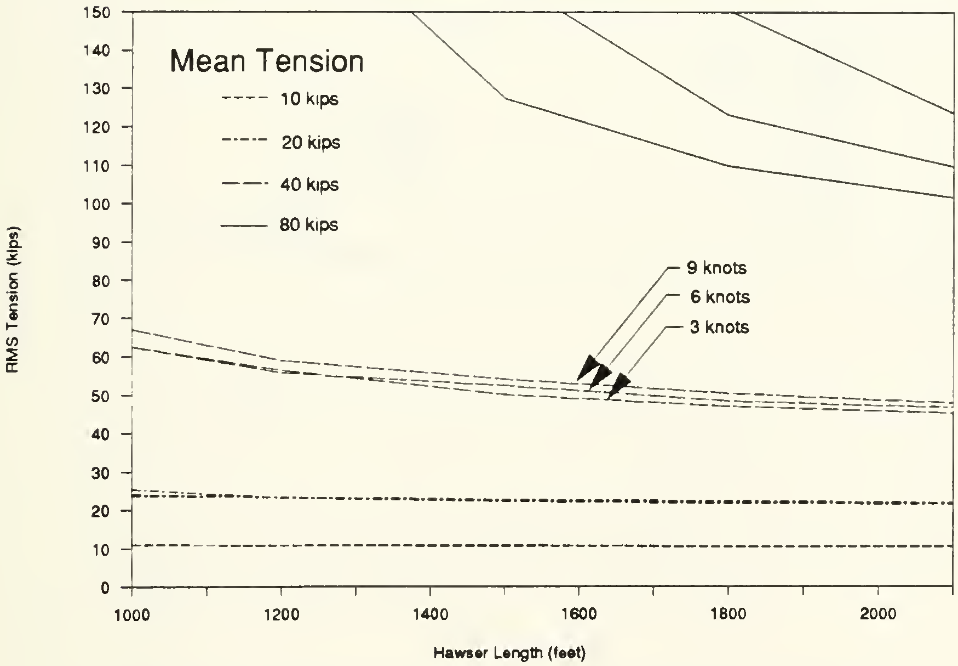

Figure B.4 ARS 52 towing AR 7 on 2.25 inch wire hawser
Relative Wave Angle 000, Wind Speed 30 knots

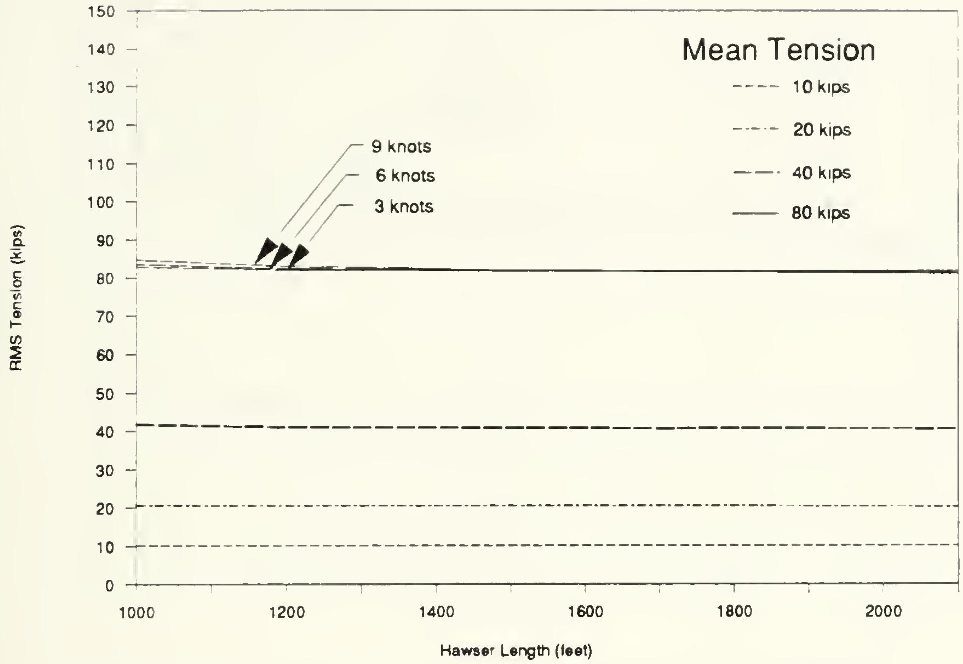

Figure B.5 ARS 52 towing AR 7 on 2.25 inch wire hawser
Relative Wave Angle 060, Wind Speed 15 knots

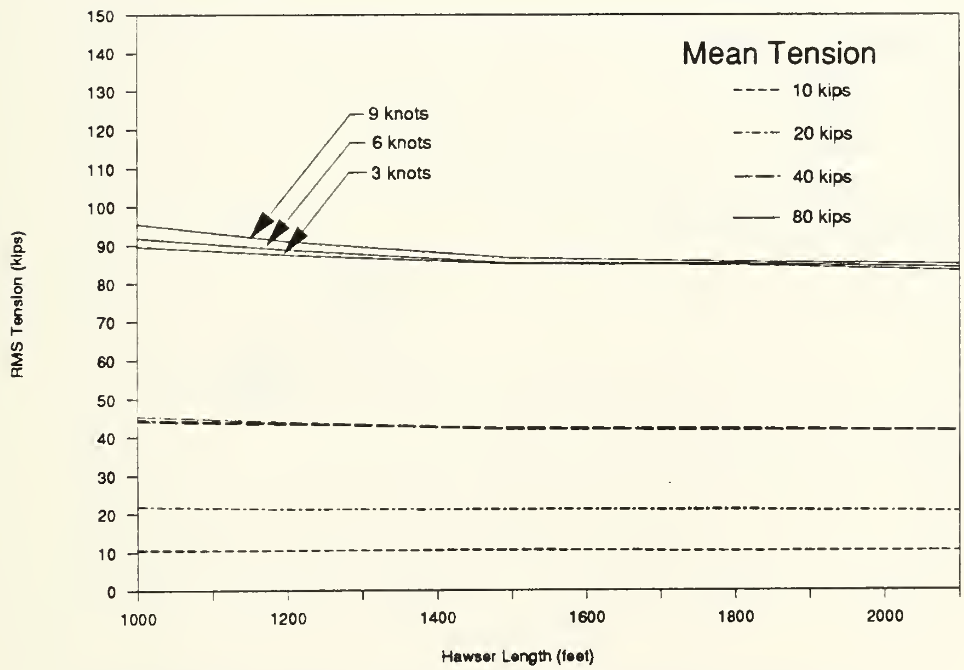

Figure B.6 ARS 52 towing AR 7 on 2.25 inch wire hawser
Relative Wave Angle 060, Wind Speed 20 knots

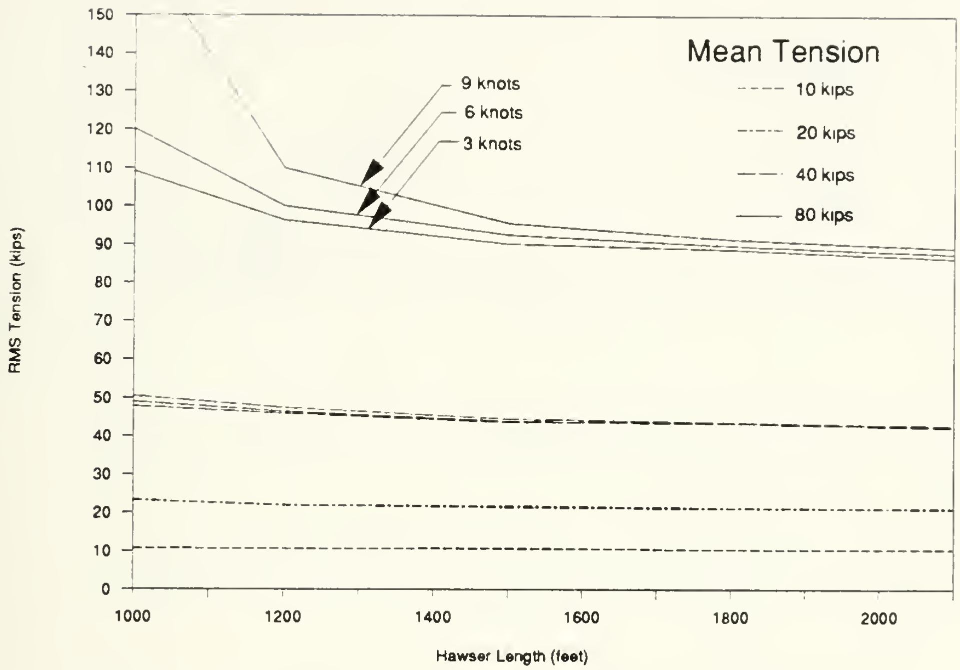

Figure B.7 ARS 52 towing AR 7 on 2.25 inch wire hawser
Relative Wave Angle 060, Wind Speed 25 knots

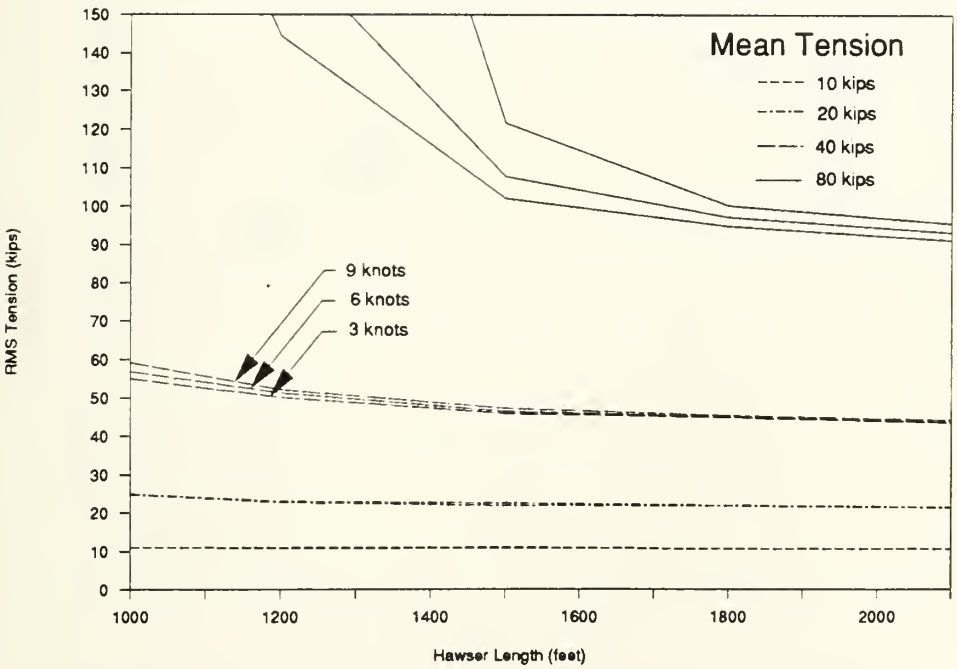

Figure B.8 ARS 52 towing AR 7 on 2.25 inch wire hawser
Relative Wave Angle 060, Wind Speed 30 knots

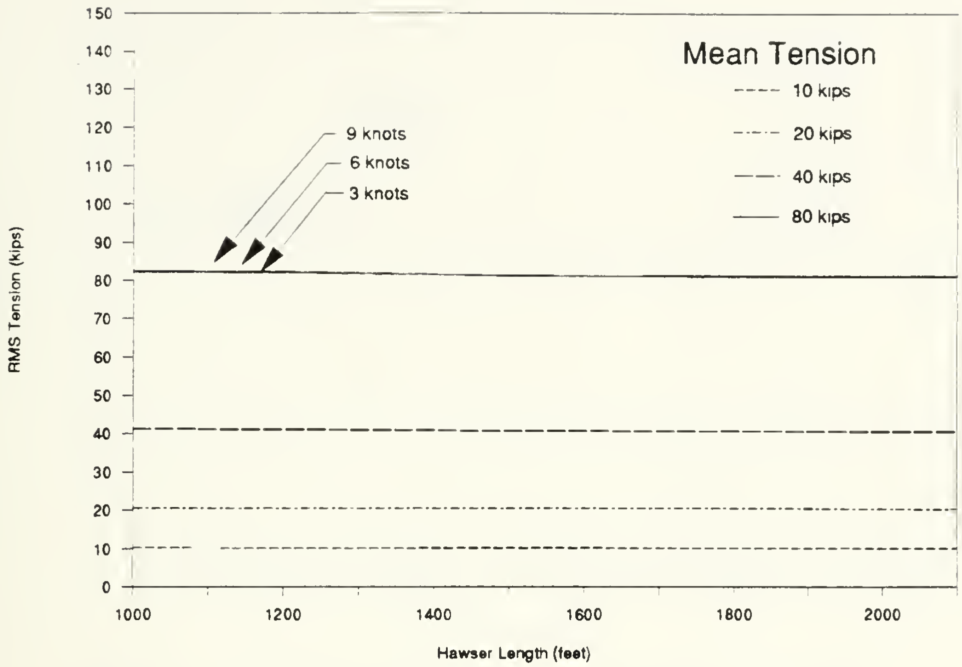

Figure B.9 ARS 52 towing AR 7 on 2.25 inch wire hawser
Relative Wave Angle 120, Wind Speed 15 knots

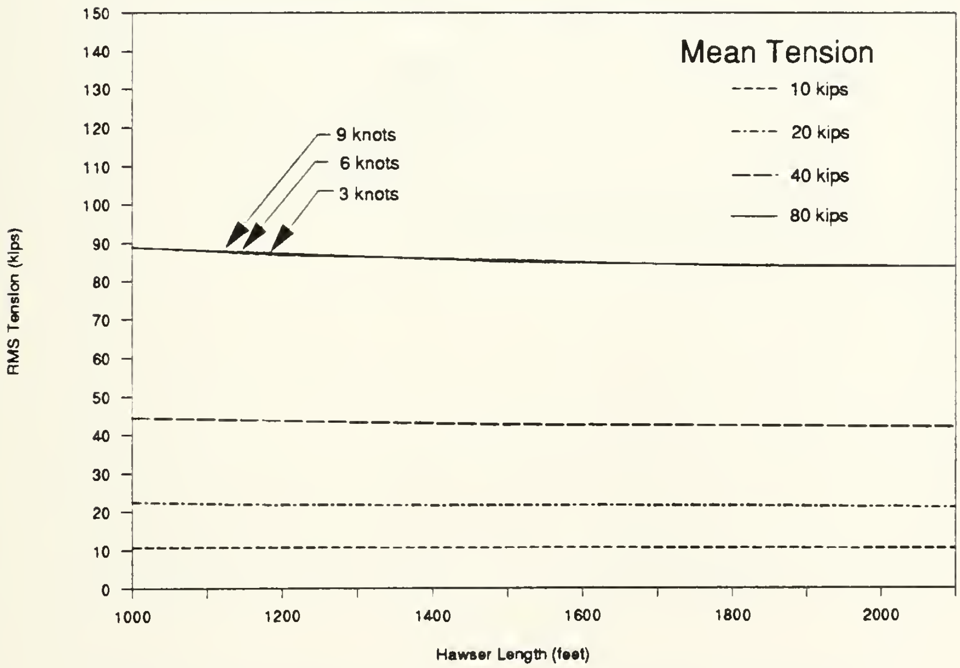

Figure B.10 ARS 52 towing AR 7 on 2.25 inch wire hawser
Relative Wave Angle 120, Wind Speed 20 knots

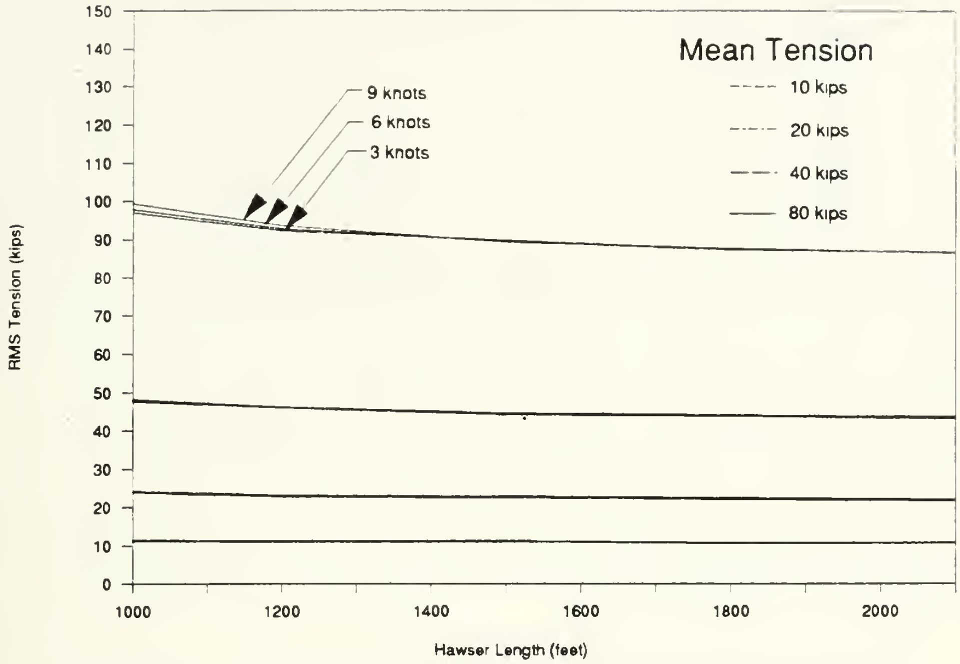

Figure B.11 ARS 52 towing AR 7 on 2.25 inch wire hawser
Relative Wave Angle 120, Wind Speed 25 knots

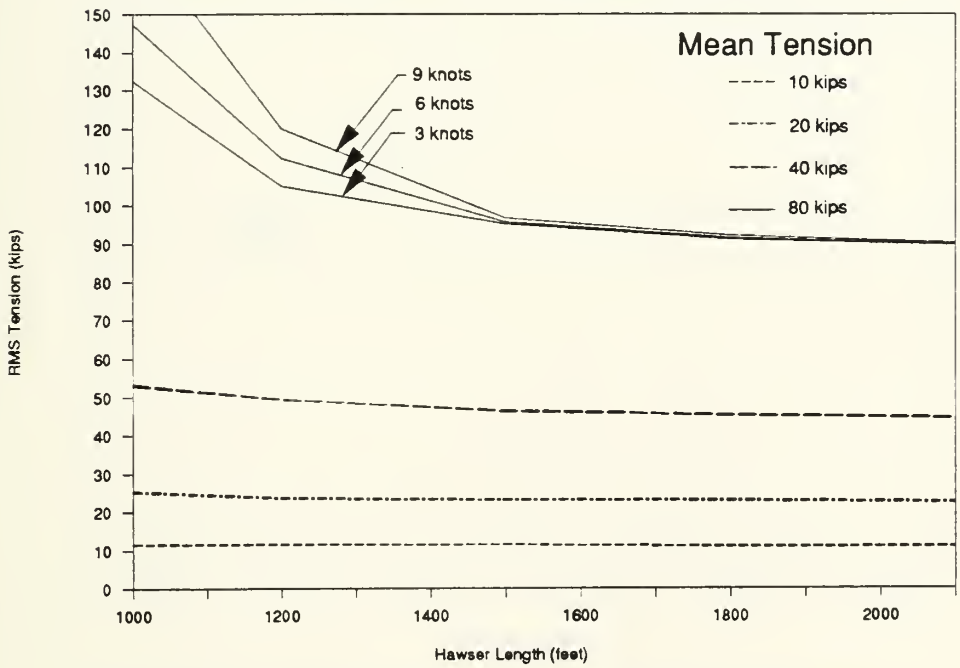

Figure B.12 ARS 52 towing AR 7 on 2.25 inch wire hawser
Relative Wave Angle 120, Wind Speed 30 knots

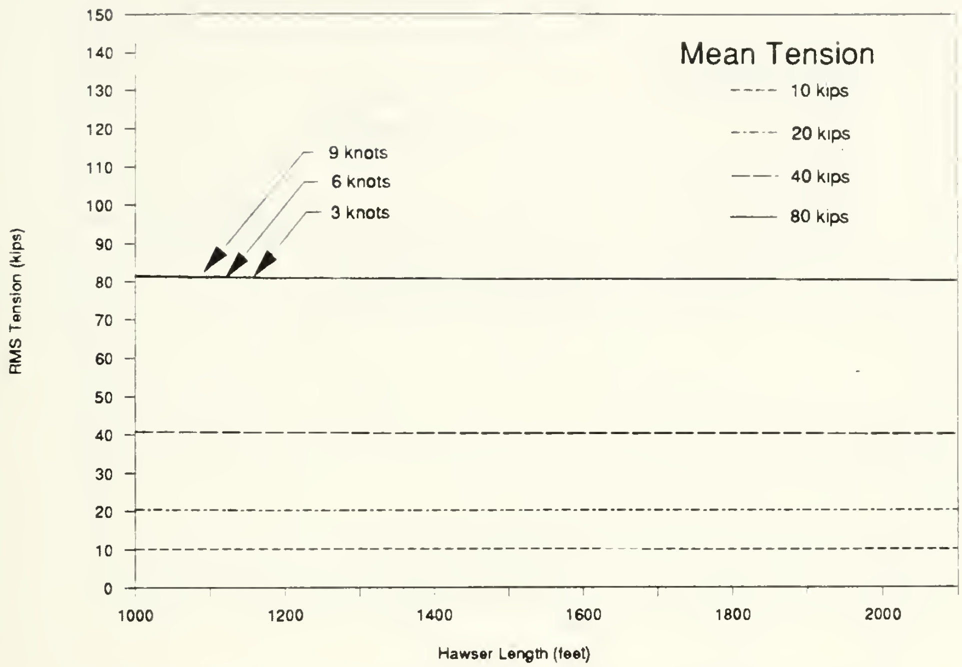

Figure B.13 ARS 52 towing AR 7 on 2.25 inch wire hawser
Relative Wave Angle 180, Wind Speed 15 knots

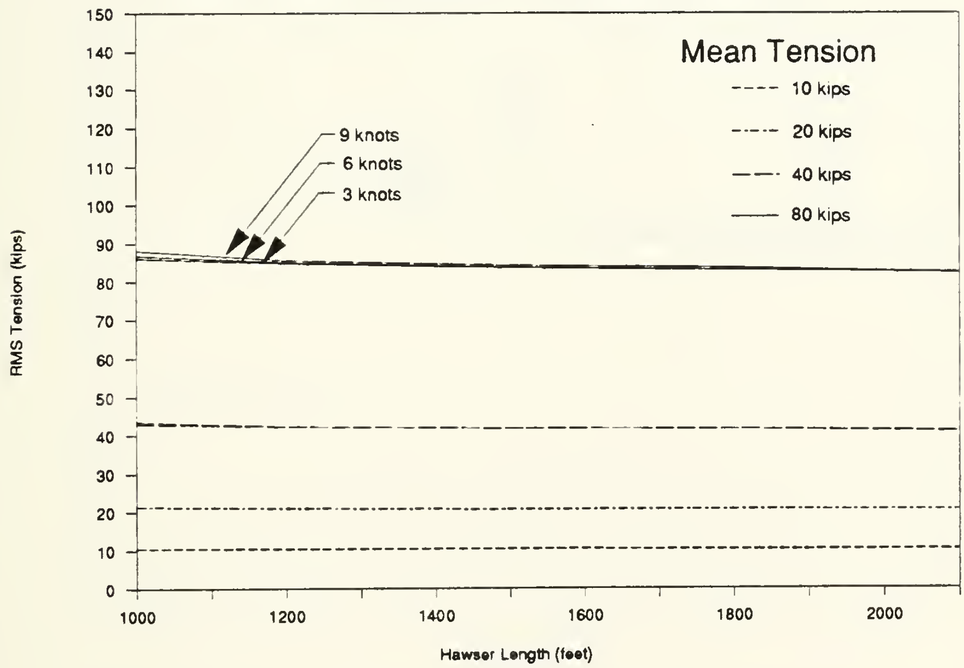

Figure B.14 ARS 52 towing AR 7 on 2.25 inch wire hawser
Relative Wave Angle 180, Wind Speed 20 knots

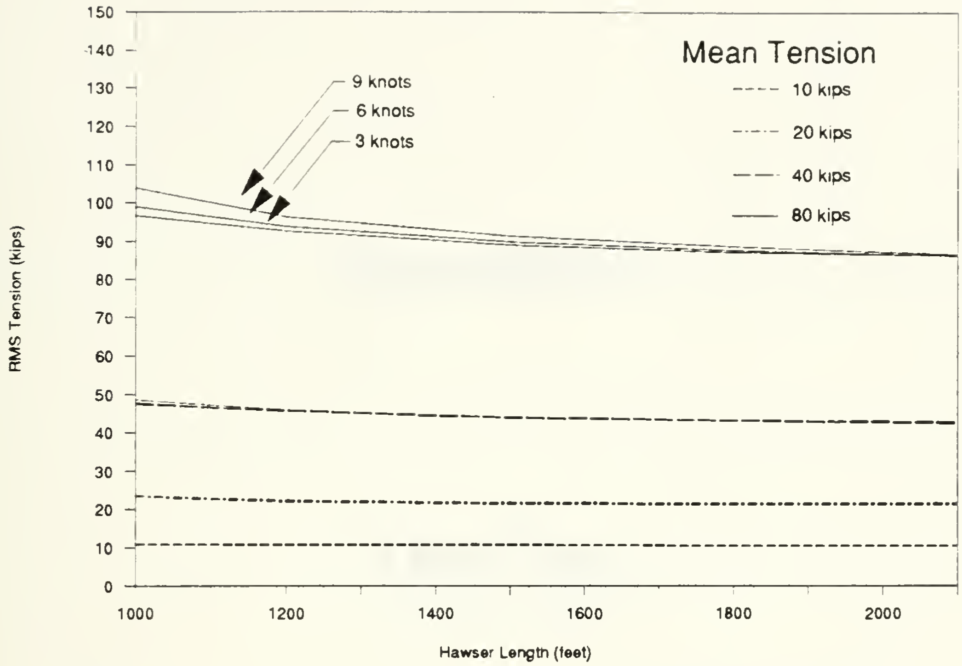

Figure B.15 ARS 52 towing AR 7 on 2.25 inch wire hawser
Relative Wave Angle 180, Wind Speed 25 knots

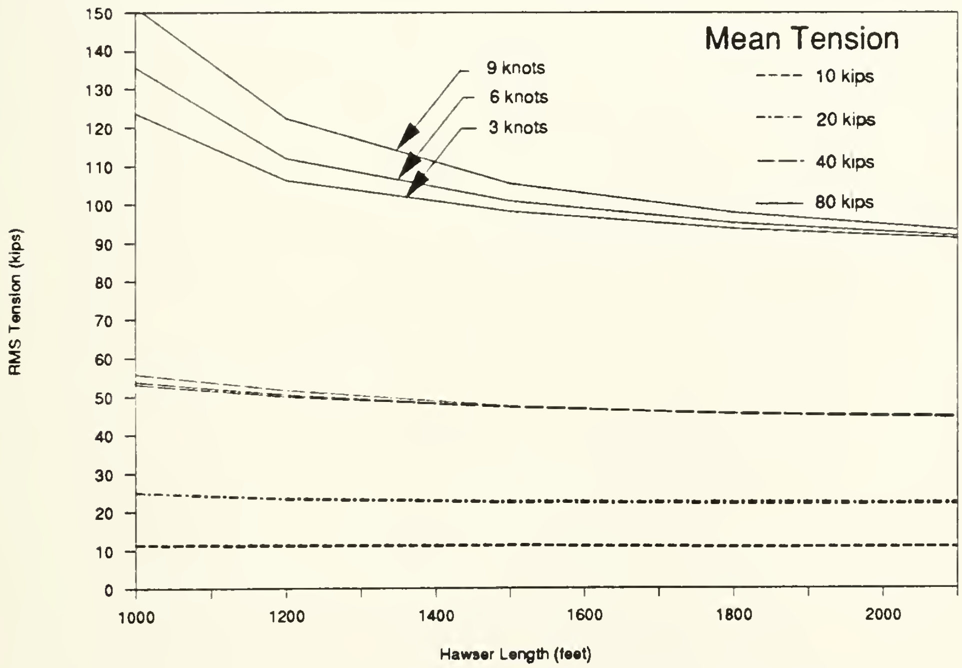

Figure B.16 ARS 52 towing AR 7 on 2.25 inch wire hawser
Relative Wave Angle 180, Wind Speed 30 knots

Appendix C

Test Plan

NAVSEA TWO BODY TOWING EXPERIMENT

TEST PLAN

REVISION 1

LT E.N. Christensen, USN

Professor J.H. Milgram

Dr. F.C. Frimm

Department of Ocean Engineering

Massachusetts Institute of Technology

26 April 1989

Chapter One

Experiment Overview

1.1 Objective

The theory for extreme towline tension statistics, developed at MIT, now forms the basis for the prediction of dynamic towline loadings experienced during open ocean towing in the U.S. Navy Towing Manual (1988). Although it is the most advanced theory currently available, it has not been validated by full-scale experiment at sea. The Two Body Towing Experiment, sponsored by the Supervisor of Salvage and Diving (NAVSEA OOC), is designed to assess the validity and applicability of this analytical method.

The Two Body Towing Experiment has been devised to acquire a large quantity of high quality data to help determine the influence of ship characteristics and environmental conditions on the dynamic tensions developed during open ocean towing. Post-voyage analysis will produce a thorough comparison to analytical predictions. It is hoped that the results of this experiment will provide a better understanding of the nature of dynamic loadings

which will allow better accuracy in predicting extreme tensions. This will not only help to improve towing safety and give operators greater confidence to tow at higher speeds when dynamic tensions are low, but perhaps allow for a reduction of the traditional factors of safety used in open ocean towing.

1.2 Participating Organizations

The Two Body Towing Experiment structural organization is shown in figure 1.1. The Supervisor of Salvage and Diving (NAVSEA OOC) is the test sponsor. The following is a summary of the organizations supporting the test and their individual responsibilities:

Department of Ocean Engineering, Massachusetts Institute of Technology (MIT):

Responsible for overall direction for test planning, conduct of operations, and data measurement. Provide data acquisition computer with software and laser range finder.

POC:	LT Erik Christensen	(617) 253-5890
	Dr. Fernando Frimm	(617) 253-5191
	Professor Jerome Milgram	(617) 253-5943

ARCTEC Offshore Corporation (AOC):

Provide and install all sensors and signal conditioning equipment and assign a field electronics technician during the testing phase.

POC:	Mr. Peter Zahn	(301) 730-1030

USS SALVOR (ARS 52):

Provide towing services in addition to logistic support services as noted in sections 5.3 and 5.4.

POC:	LCDR Bob Reish	(808) 471-0123

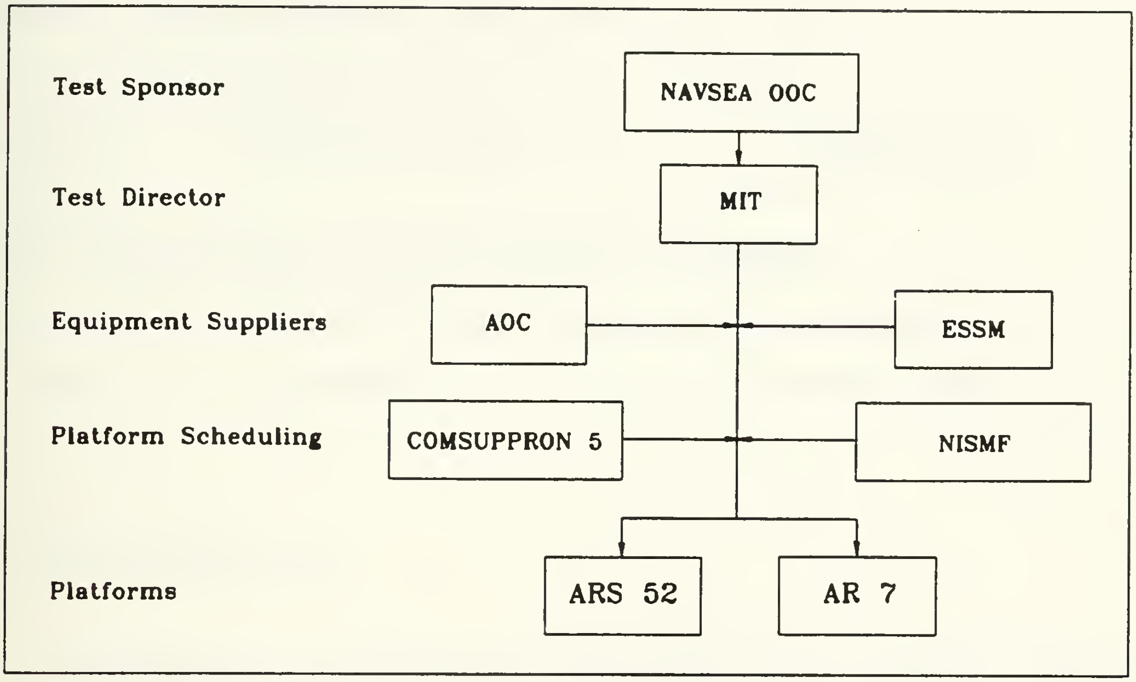

Figure 1.1 Structural Organization

Global Phillips Cartner (ESSM Williamsburg):

Provide one tension load cell to be used on the tug. ESSM is an indirect participant; AOC will be responsible for installing and operating their equipment.

POC: Mr. Tom Oster (804) 887-7402

Supervisor of Salvage and Diving (NAVSEA OOC):

Provide one portable LORAN C receiver with computer interface box. NAVSEA OOC is an indirect participant; MIT will be responsible for installing and operating their equipment.

POC: Mr. Bob Whaley (202) 697-7403

Commander, Support Squadron 5 (COMSUPPRON 5):

Schedule a tug for the experiment.

POC: LT Karen Kohanowich (808) 474-7769

Inactive Ship Maintenance Facility, Pearl Harbor, HI (NISMF):

Provide the ex-USS HECTOR (AR 7) configured with a towing bridle.

POC: Mr. Lee Cobb (808) 471-4547

1.3 Test Platforms

The characteristics of the two platforms participating in the test are shown in Table 1.1 and described below.

Table 1.1 Gross Characteristics of Test Platforms

	TUG	TOW
Ship	ARS 52	AR 7
Length (ft)	255	520
Beam (ft)	52	73
Draft (ft)	15.5	15.5
Displacement (Ltons)	2,850	10,130

1.3.1 Tug

The USS SALVOR (ARS 52) is a "Safeguard" Class Salvage ship. Commissioned on 14 June 1986, the SALVOR is a member of the newest class of salvage ship in the U.S. Navy inventory. She is powered by four Caterpillar D-399 diesel engines which produce a total of 4200 SHP. The SALVOR has an Almond A. Johnson Series 322 automatic towing machine which holds 3000 feet of 2.25 inch wire towing hawser and has a traction winch for 14 inch fiber rope hawsers. The SALVOR is capable of producing 138,000 pounds of bollard pull thrust.

1.3.2 Tow

The ex-USS HECTOR (AR-7) is a "Vulcan" Class Repair Ship commissioned on 7 February 1944. She was recently decommissioned from the U.S. Navy inventory and is in the process of being leased to the Pakistani Navy through the Foreign Military Sales Program. The HECTOR is currently in the custody of the Inactive Ship Maintenance Facility, Pearl Harbor, Hawaii. Permission has been obtained from the Office of the Chief of Naval Operations (CNO) to use the HECTOR prior to that transfer.

Chapter Two

Data Products

2.1 Data Collection

Data collection will focus on tension measurements using two tension sensing load cells with simultaneous measurement of various parameters affecting dynamic tension extremes. All data is to be collected at one data acquisition site in digitized form and recorded on diskettes compatible with the IBM-PC standard to allow immediate playback and complete post-voyage analysis. Table 2.1 shows all parameters that will be simultaneously recorded on the primary data acquisition system computer. As an additional measure of redundancy and to provide a quick means of verifying recorded data, the output from various installed shipboard sensors will be manually recorded. It is requested that tug personnel assist in the data collection effort by manually recording the data shown in table 2.2 and as noted in section 5.3. Enclosure (1) is provided to assist in this effort.

Table 2.1 Primary Data Collection

PARAMETER	LOCATION	INSTRUMENT
Wind Speed	tug	portable anemometer
Wind Direction	tug	portable wind vane
Heading	tug, tow	flux gate compass
Hawser Tension	tug, tow	tension link
Hawser Angle	tug, tow	hawser angle indicator
Surge	tug, tow	6 DOF motions package
Sway	tug, tow	6 DOF motions package
Heave	tug, tow	6 DOF motions package
Roll	tug, tow	6 DOF motions package
Pitch	tug, tow	6 DOF motions package
Yaw	tug, tow	6 DOF motions package
Wave Height	tug	Doppler radar sensor
Speed	tug	LORAN receiver
Range	tug	laser range finder

2.2 Instrumentation

The instrumentation to be used during the Two Body Towing Experiment is summarized in figure 2.1 and discussed below. All measurements made on the tug will be directly coupled to the primary data acquisition unit using coaxial cables. A redundancy in the recording of all measurements is desirable and considered necessary to provide a measure of safety in

Table 2.2 Manual Data Collection

PARAMETER	INSTRUMENT	FREQUENCY
Wind Speed	installed sensor	10 minutes
Wind Direction	installed sensor	10 minutes
Ship's Position	LORAN, SATNAV, visual	10 minutes
SOG	LORAN, SATNAV, visual	10 minutes
COG	LORAN, SATNAV, visual	10 minutes
Speed	installed sensor	10 minutes
Wave Height	seaman's eye	hourly
Hawser Length	visual	all changes
Shaft rpm	installed sensor	all changes
Propeller Pitch	installed sensor	all changes
Ordered Course	---	all changes
Ordered Speed	---	all changes

the event of data transmission problems. Therefore, all measurements made on the tow will be recorded locally on a personal computer and simultaneously telemetered to the tug via an FM telemetry system. Software routines will allow active monitoring of all measurements on a real-time basis and provide online comparison to analytical predictions to assess the validity of recorded data.

2.2.1 Wind

A portable anemometer and wind direction vane will be manually installed on the tug by AOC personnel. The most important aspect of wind measurement is the sensor location: the

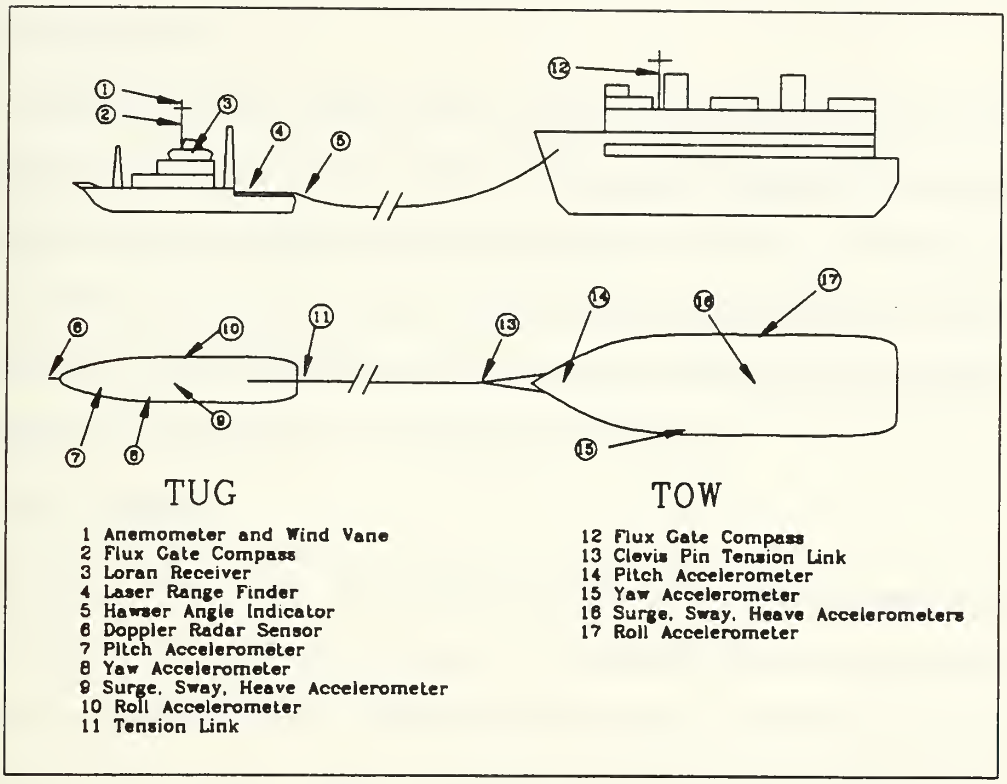

Figure 2.1 Sensor Location

unit must be installed in a position that is unobstructed from all directions. This will require that the unit be placed high on top of one of the masts such that it is above wind separation regions in all directions. The output will be wired directly to the data acquisition computer. To maintain redundancy in the data collection effort and to provide a means of quick cross check reference, both the wind speed and direction, as indicated on the ship's installed sensors, will be manually recorded every ten minutes by ship's personnel.

2.2.2 Ship Speed

A portable LORAN C receiver will be installed on the tug by MIT personnel. The unit will provide both a digital readout of latitude and longitude and an RS-232 computer output for direct recording of information onto the data acquisition computer. To maintain redundancy and provide a quick cross check reference, the speed indication from the ship's installed speed log and computations of speed over ground (SOG) between successive navigation fixes will be recorded manually every ten minutes.

2.2.3 Wave Height

A portable Doppler radar sensor will be mounted on a metal pipe extending approximately ten feet forward of the bow of the tug. The unit will measure the Doppler shift of a microwave radar emission that is bounced off the sea surface. The motions of the ship will be decoupled from the data through an internal gyroscopes. The output signal will be connected directly to the data acquisition computer. To maintain redundancy in the data collection effort and to allow a means of quick cross check reference, a visual estimate of the wave height, based on an experienced "seaman's eye," will be manually recorded at the start and completion of each test run by ship's personnel. As the ship pitches and rolls and travels through the water it radiates energy into the water in the form of waves. Unless an on-site calibration procedure is performed, the influence of these ship generated waves can severely corrupt wave height measurements. The calibration of this sensor involves comparison of data measured in the vicinity of a "reference" wave height sensor. Chapter 6 provides additional information and details on performing this calibration.

2.2.4 Motions

A six degree of freedom (DOF) motion sensing package will be installed on both the tug and the tow by AOC personnel. The main unit, consisting of a vertical referenced gyroscope and three accelerometers, will be mounted near the ships center of gravity (CG) and used to measure translational motions (surge, sway, and heave.) Three other servo accelerometers, each enclosed in individual weather-tight containers, will be mounted at known locations from the main unit and measure rotational motions (roll, pitch, and yaw.) On the tow, all accelerometers will be wired to a data recorder and FM telemetry system. On the tug, all accelerometers will be wired directly to the main data acquisition unit.

2.2.5 Heading

Portable flux gate compasses will be mounted on both the tug and tow to provide a continuous record of the dynamic, time-varying heading of both vessels. Since the compass is sensitive to magnetic fields, any magnetic disturbance near it cause a deflection from the proper reading. To minimize the effects of residual magnetism of the ship, the flux gate compass should be installed in a spot where the magnetic field is uniform so that the local magnetic field lines will only change slowly; as far as possible from the nearest metal surface in a location which does not have sharp edges or corners which could cause the field direction to change rapidly. The optimum location for installation of these units will have to be determined after an on-site inspection. The output from these will be sent directly to the main data acquisition computer. To compensate for the errors produced by the ship's magnetic signature, both compasses must be calibrated after installation and their deviation computed. This will require that both vessels be "swung" so that the indicated magnetic heading

on the flux gate compasses can be compared to the installed magnetic compass on board the tug for various courses. Chapter 6 provides additional information and guidelines for conducting this procedure.

2.2.6 Tension

Strain gaged tension links will be used to measure the dynamic tensions developed at both ends of the hawser. On the tug, the tension will be measured from a 160 kip load cell attached to the hawser using a carpenter stopper as shown in figure 2.2. Installation will be performed by AOC with assistance from the crew of the tug. Coaxial cable will run directly from the tension link to the data acquisition unit. Since the towing load will be taken up by the load cell, the ship's installed tensiometer will be inoperative during testing. On the tow, tension will be measured from a 180 kip waterproof load cell mounted in a clevis pin connected to the flounder plate of the towing bridle as shown in figure 2.3. Data will be recorded locally and telemetered to the main data acquisition unit.

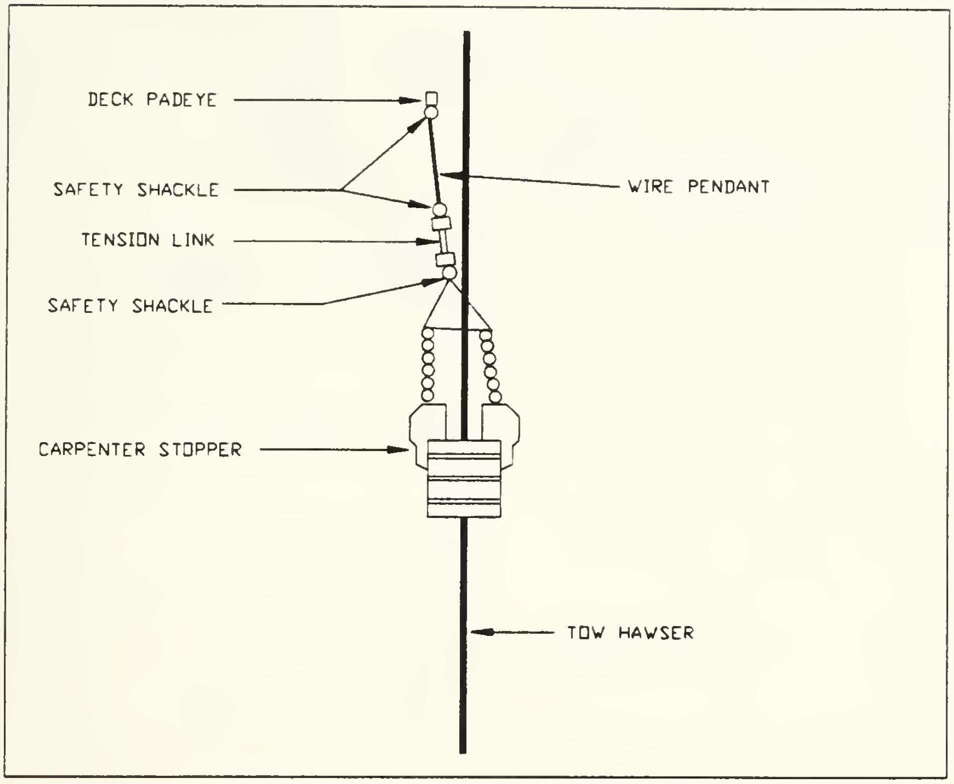

Figure 2.2 Tug Towing Configuration

2.2.7 Range

The distance between the two vessels will be continuously measured using a handheld laser range finder. The unit is approximately the size of a large pair of binoculars (11.4" x 9.4" x 3.3"), weighs 8.2 pounds, and is powered by normal ship's power (120 VAC). It will be mounted on a tripod and manually trained on a reflector positioned on the bow of the tow using an integrated telescopic lens. Distance is simultaneously displayed in the view finder and output directly into the data acquisition unit via coaxial cable.

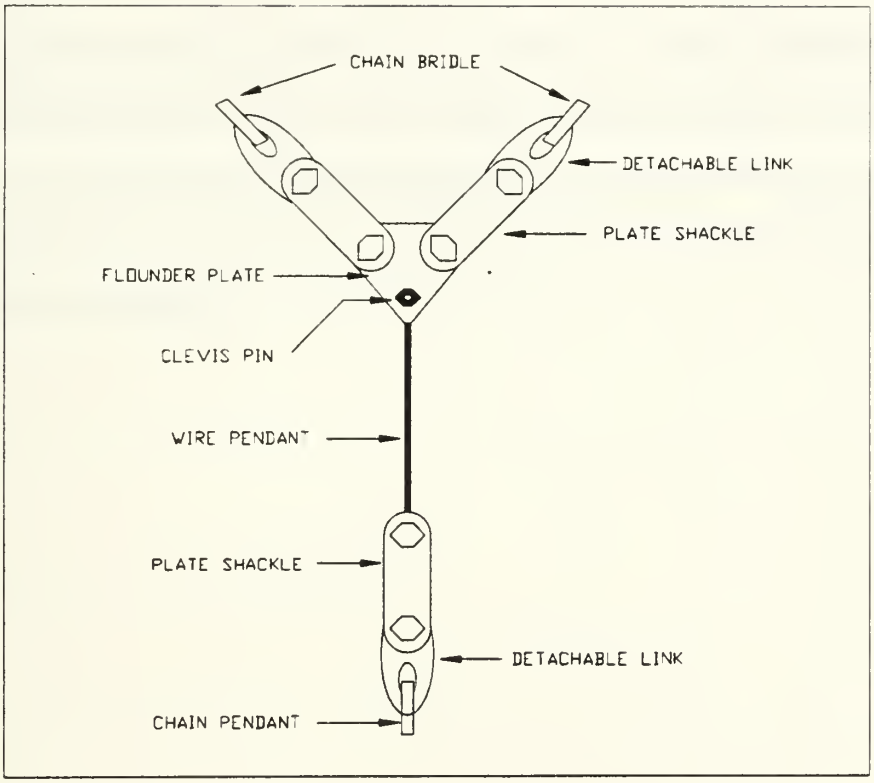

Figure 2.3 Towing Bridle Configuration

2.2.8 Hawser Angle

The towing hawser azimuth angle indicators will be installed on the fantail of the SALVOR and on the bow of the HECTOR by AOC personnel. These indicators use string potentiometers to measure the vertical and horizontal angular displacement of the towline.

2.2.9 Hawser Length

The exact length of towing hawser is to be measured by visual verification as it is paid out from the towing machine. Using a known length, such as the distance from the towing H-bits to the stern roller, the towing machine operator can record the number of lengths of cable subsequently paid out or taken up. Comparison with the installed shipboard sensor should be done for redundancy.

Chapter Three

Schedules

3.1 General Test Schedule

Table 3.1 provides a schedule of major events for this exercise.

Table 3.1 SCHEDULE OF EVENTS

DATE	LOCATION	SHIP	EVENT
May 4 - 7	inport	AR 7	• sensor installation
May 8 - 9	inport	ARS 52	• sensor installation
May 10 - 12	at sea	ARS 52	• calibration procedures
May 13 - 14	inport	ARS 52 & AR 7	• system verification • dry run test of all sensors
May 15 - 18	at sea	ARS 52 & AR 7	• wire rope data collection
May 19	at sea	ARS 52 & AR 7	• fiber rope data collection
May 20 - 22	inport	ARS 52 & AR 7	• demobilization

3.2 Sensor Installation

The installation of sensors, as shown in figure 2.1, will occur inport during the period May 4 - 9. AOC will be responsible for the majority of the instrumentation and will have a small contingency of technicians available to perform this work. It is requested that they be given free access to both ships while installing equipment.

3.3 At-sea Calibration

The initial at-sea period will be used for calibration of the wave height sensor and the flux gate compass. Only the SALVOR is required for this procedure. The details of conducting the calibration are provided in chapter 6. Upon returning to port from this phase, it is requested that the SALVOR moor in close proximity to the HECTOR to assist in the system verification procedures.

3.4 System Verification

Although the at-sea calibration procedure will afford the opportunity of verifying many of the sensors installed on the tug, a complete end-to-end test of all sensors must be performed before commencing the experiment. The total data acquisition and instrumentation lineup will be verified with data from all sensors being simultaneously recorded during the period May 13 - 14.

3.5 At-sea Data Collection

The daily test schedule is outlined in table 3.2 and described below. Primarily for personnel safety, the test is only to be conducted during daylight hours. Preparations will commence at 0700 daily when the length of towing hawser will be verified and both the hawser angle indicator and the deck tension link will be reinstalled with assistance from the ship's crew. A small boat, provided by the SALVOR, will be used to ferry the technician to the tow. Once on the tow, the technician will start up the portable generator and energize all transducers and signal conditioning equipment. The data acquisition station operator on the tug will visually verify receipt of all local and telemetered signals before the actual data collection will commence.

After confirming that all transducers are operational, the experiment supervisor will inform the Officer of the Deck (OOD) that data recording is ready to commence. Each segment of uninterrupted data collection should last approximately 30 to 45 minutes. The experiment supervisor will inform the OOD upon completion of each segment of the experiment.

Upon completion of each day's data collection, at approximately 1900, the technician on the tow will de-energize all equipment and a small boat will ferry him to the tug. On the tug, all transducers and signal conditioners will be de-energized and the data collection sheets will be collected from the ship bridge team. Each evening, an analysis of all sampled data will be conducted to reconfirm the validity of all recorded data. The towing experiment

supervisor will inform the Commanding Officer and ship's navigator of the requested sea conditions for the following day's data collection so that appropriate navigational tracks can be laid out.

3.6 Demobilization

The last two days of the experiment will be used to remove all sensors from both vessels and prepare the instruments for shipment back to their parent organizations. Initial demobilization can begin while at sea upon completion of data collection.

3.7 Contingency Plans

In the event of equipment malfunction or deteriorating weather conditions, modification to the events in this schedule will be made on a case-by-case basis. A conscious effort has been made to ensure sufficient redundancy in recording of data to minimize the effects of equipment failure. Since the vast majority of equipment is to be provided by AOC, the presence of one of their electronic technicians, who is familiar will all sensors used, is considered very prudent. In addition, both MIT and AOC will have a quantity of spare parts on hand to allow at-sea replacement rather than requiring assistance from ashore.

Table 3.2 Daily Test Schedule

EVENT	TIME	ACTION
SETUP	0630	• launch small boat
	0700	• send technician to tow • energize all instruments
	0730	• verify signals from all sensors
DATA COLLECTION	0800	• ship turn to desired course • seakeeping test • elastic wave test • transient response test
SECURE	1700	• launch small boat • de-energize all instruments • obtain copies of all logs • remove carpenter stopper
	1730	• retrieve technician from tow
DATA ANALYSIS	1900	• preliminary data verification • preparations for next day
	2000	• discussion with CO/Navigator

Chapter Four

Tow Test

4.1 Overview

The primary purpose of this experiment is to measure the dynamic tensions developed in a wire towing hawser while towing in the open ocean. By measuring all factors that influence towline tension, the analytical models can be verified step-by-step. A series of seakeeping tests have been designed to accomplish this. In addition, four other tests have been developed to supplement the data collection effort. This will provide a wealth of information for post voyage analysis. However, at no time should the successful completion of the seakeeping test be jeopardized by the accomplishment of any of these secondary tests.

4.1.1 Seakeeping Test

GOAL: to assess the validity of current analytical models in predicting tension extremes and ship response to environmental conditions during towing.

PROCEDURE: A series of test runs will be performed varying a different parameter each time. Ideally, the test should be performed in two different sea states with

four towing angles, three towline lengths at two different speeds. However, this would require a total of 48 test runs which would take well in excess of one week of at-sea measurement. Acceptable results can be obtained by conducting only a select portion of these provided that each parameter is varied sufficiently to identify trends and allow correlation with analytical predictions. Each test run should be done at constant speed and heading with data recorded continuously for 30 to 45 minutes. The first five minutes of each run will be used to verify that all sensors are operating correctly. The individual ship headings will be determined based upon local conditions to obtain the proper angle with respect to the waves during data recording. It is requested that the tug only maneuver as necessary to avoid navigation hazards or other shipping. Should the ship be required to maneuver during data collection, the experiment will be halted and that portion repeated. During each test run, the data acquisition team will monitor and record all parameters shown in table 2.1. To maintain redundancy in the data collection effort and to allow a means of quick cross check reference, it is requested that the SALVOR's navigation team manually monitor and record the parameters shown in table 2.2 using enclosure (1).

4.1.2 Towing Machine Test

GOAL: to measure the dynamic response of the towing machine while towing in the automatic mode.

PROCEDURE: Conduct one of the seakeeping tests, as discussed above, with the towing machine in the automatic mode. By adjusting the pay out release tension on the towing machine to a value just above the predicted RMS tension value for the specific scenario, the towing machine should automatically

pay out and retrieve the towing hawser as the dynamic tensions fluctuate above and below the preset limits. Since the carpenter stopper cannot be used on the fantail of the tug to connect the tension link to the towing hawser, all tension measurements will be made from the tow end of the hawser. If possible, the electrical signal to the ship's tensiometer will be recorded along wiih the drum position. Immediately following this test, reinstall the carpenter stopper and repeat the test with the same conditions.

4.1.3 Fiber Rope Test

GOAL: to assess the validity of current analytical models in predicting the tension extremes developed while towing with synthetic (fiber) towing hawsers.

PROCEDURE: Conduct several seakeeping tests, as discussed above, while towing on a fiber towline. This is planned for the last day of the at-sea data collection period. Initially, the tow will have to brought into "short stay" so that the chain pendant at the end of the wire towing hawser is retrieved on the fantail of the SALVOR. The wire hawser is to be removed and a 14 inch fiber towline is to connected to the chain pendant then streamed astern. These tests should be conducted at two different speeds (6 and 9 knots) and two different lengths (1000 and 1500 ft).

4.1.4 Elastic Wave Test

GOAL: to attempt to determine if elastic waves are present and, if so, to measure and record their existence. If excited at sufficiently high frequency, a cable may develop elastic waves which may not be visible by the naked eye. An evaluation of any elastic wave data collected will be performed in post-voyage analysis.

PROCEDURE: The elastic wave test is to be conducted for a total of five minutes immediately following with the seakeeping test. The only change from the seakeeping test will be to raise the sampling frequency to 10 Hz and increase the cutoff frequency to 3.3 Hz. It is requested that the SALVOR continue on the specified test run track and continue monitoring parameters as with the seakeeping test.

4.1.5 Transient Response Test

GOAL: to measure and record the response of the towing system during speed changes.

PROCEDURE: Starting from just bare steerage, the ship's propeller pitch setting is to be increased to pre-determined settings to yield final speeds of 3, 6, and 9 knots. Data should be collected continuously for six minutes at each speed. The transient response test should be done in calm water (significant wave height less than two feet) at three different towline lengths (1000, 1500, and 2100 feet) at the conclusion of the seakeeping and elastic wave tests. All data recording will be performed by the data acquisition team.

4.2 Conduct of the Tests

The most labor intensive aspect of changing the towing configuration between successive runs is changing the length of the towing hawser paid out since it will require manual resetting of carpenter stopper, careful measurement of hawser scope, and realignment of hawser angle indicators. Therefore, it is recommended that initially, the hawser length be kept constant and the other parameters (speed, sea state, and relative wave angle) be varied.

Table 4.1 provides a tentative sequence of events to minimize labor between runs. Local environmental conditions will dictate the optimal sequence and may require significant changes to the proposed testing order. The test supervisor will rely heavily on the experience of the Commanding Officer and navigation team to select the optimum locations for the experiment. Three different lengths (1000, 1500, and 2100 ft), two different speeds (3 and 9 knots), and two different sea states (sea states 3 and 5) are to be investigated. In addition, the influence of different wave angles will be considered.

During open ocean towing, it is standard practice to regularly "freshen the nip." This involves shifting the point of contact of the towing hawser on the stern roller to minimize wear by either paying out or hauling in the towing hawser a few feet. It is requested that no such adjustments be made during data collection periods (0700 to 1900) as this would cause excessive delays in the experiment as it would necessitate a readjustment of the carpenter stopper and towing hawser angle indicator and careful measurement of the scope paid out.

4.3 Safety Precautions

As with all towing operations, one of the major safety concerns is the parting of the hawser while under tension. Since the bollard pull of the SALVOR is rated at 138 kips and the rated breaking strength of its 2.25 inch towing hawser is 444 kips (U.S. Navy Towing Manual, 1988), the likelihood of hawser breakage during this experiment is small. However, since dynamic tension surges can far exceed normal towing tensions, the possibility hawser breakage cannot be completely dismissed. Since tensions will be continuously monitored by the data acquisition computer operator, precautionary measures shall be taken if tensions exceed predictions.

Table 4.1 Test Runs

RUN	LENGTH	SPEED	SEA STATE	RELATIVE WAVE ANGLE
1	2100	6	5	000
2	2100	6	5	060
3	2100	6	5	180
4	2100	8 - 9	3	000
5	2100	8 - 9	3	060
6	2100	8 - 9	3	120
7	2100	*	2	000
8	1500	6	5	000
9	1500	6	5	120
10	1500	6	5	180
11	1500	8 - 9	3	000
12	1500	8 - 9	3	060
13	1500	8 - 9	3	120
14	1500	*	2	000
15	1000	6	5	000
16	1000	6	5	060
17	1000	6	5	180
18	1000	8 - 9	3	000
19	1000	8 - 9	3	060
20	1000	8 - 9	3	120
21	1000	*	2	000

Note: * various speeds (Transient Response Test)

Primarily for personnel safety, the Two Body Towing Experiment will only be conducted during daylight hours. As an added precaution, it is requested that all personnel not directly involved with the towing experiment be restrained from the fantail during the experiment.

Except in emergency towing, it is normal U.S. Navy practice to tow only unmanned tows. However, it is highly desirable to have a technician on the tow for the duration of each day of towing to monitor the operation of all sensors and make immediate on-the-spot corrections. In the event of rough seas making it unsafe to board or keep the tow manned, it is requested that the ship maneuver to a calm region just long enough to allow the technician to safely board the tow and energize all equipment. The tug can then tow the unmanned vessel into rougher waters for data measurement.

Chapter Five

Logistic Support

5.1 Navigation

No specific operating area (OPAREA) has been designated for this experiment. However, in order to achieve meaningful results, the wind speed and seas must be sufficient magnitude to create dynamic tensions large enough for proper data analysis. Based on analytical studies and previous experimental results, wind speeds greater than 15 knots and wave heights greater than four feet are required. Each individual data collection phase of the experiment will require the ship to maintain course and speed for approximately 45 minutes while data is recorded. At all times, it is highly desirable to operate in regions away from major shipping lanes to reduce the probability of having to adjust course or speed during a data run.

5.2 Communications

Two separate communication channels should be used in this experiment: one dedicated to continuous data telemetry from tug to tow and the second for the test participants to use for technical discussions and boat handling. AOC will provide a 14 channel FM-FM telemetry system operating a frequency of 259 MHz. It is requested that the tug provide a means of VHF communications for the technical discussions and boat handling.

5.3 Data Collection

To assist with the interpretation of test results, the SALVOR is requested to manually record the following data items. A sample data collection worksheet is provided in enclosure (1) to assist in this effort.

1. **Navigation Data**

   a. Log vessel's position at the begining, end, and every ten minutes during data collection using, in order of preference, SATNAV, visual, or dead reckoning (DR) fixes.

   b. Log all speed and course changes.

2. **Ship Operating Conditions**

   a. Log the rpm of both shafts during each run.

   b. Log the pitch settings of both propellers during each run.

   c. Log the ship's speed, as read from the installed speed log, every ten minutes

3. Environmental Data

a. Log wind speed and direction, as read from installed shipboard sensors, every ten minutes.

b. Log an estimate of the wave height, using seaman's eye, at the beginning and end of each data run.

4. Towing Hawser Log

a. Provide a copy of towing hawser log entries for each day of testing. During testing, the load will be taken up by the tension link used in the experiment and so the shipboard tensiometer will not be operational. The experiment supervisor can provide the towing machine operator with tension measurements as required for entry into the towing hawser log.

5.4 Support Services

During the at sea portion of the experiment, it is requested that the SALVOR provide the following support items:

1. Assist in locating desirable areas of higher wind speeds and minimal traffic to conduct each day's testing. The experiment supervisor will provide specific requests to the navigator and commanding officer each night after review and analysis of collected data.

2. Supply one small boat (Whaler or ZODIAC type) and operator to transport a technician to and from the tow daily as needed. During all data collection periods, it is highly desirable to have one person on board the tow to monitor the sensors and ensure data is being recorded locally. Since no power will be available on the tow, all equipment placed on board will be powered by a portable generator installed and operated by AOC.

3. Provide berthing and messing for three test participants; test director, test conductor, and technician.

4. Provide a dedicated location inside the ship, preferably near the fantail, with a table and desk to install a data acquisition system consisting of two personal computers (IBM PC), monitors, keyboards, portable LORAN receiver, and FM telemetry receiver. All data collected on the tug will be connected to the data acquisition system using coaxial cables. Each night, preliminary data analysis and verification will be conducted here.

5. Provide an accurate measure of the amount of towing cable paid out past the stern of the tug. Although the installed shipboard sensor can be used, its accuracy cannot be guaranteed without conducting a calibration procedure. Instead, the primary means of measuring the length of towing hawser paid out will be by visual measurement as described in section 2.2.9.

6. Provide a copy of the current deviation table for the magnetic compass installed on the bridge of the tug. This will be used as the reference for the determination of the deviation of the portable flux gate compasses during the swing ship procedure.

7. Provide one carpenter stopper, wire rope pennant and safety shackles to connect the hawser as shown in figure 2.3. It is requested that the tug provide manpower assistance in rigging this stopper during the experiment. It must be removed whenever the length of cable is changed or when the ship "freshens the nip". Whenever installed, the shipboard tensiometer will be inoperative as the load cell connected to the carpenter stopper will be handling all the load. The experiment supervisor will provide any tension information needed for entry in the towing hawser log.

8. Provide a means of portable VHF communications between the technician on the tow and the data acquisition site on the tug. This radio net will be used for technical discussions.

9. Assign one crew member to assist in the data collection effort. This will involve maintaining a continuous visual sighting of the reflector on the bow of tow using the portable laser range finder.

10. Provide assistance in demobilization of sensors upon completion of the experiment.

Chapter Six

Calibration Procedures

6.1 Wave Height Sensor

6.1.1 Overview

Since the purpose of this experiment is to collect data to validate analytical models, accurate measurement of all factors influencing towline tension is essential. Dynamic towline tensions are the result of hawser elongations caused by seakeeping motions of both ships in response to sea conditions. The two main influences on local sea conditions are wind and wave actions. Although the instrumentation installed for this experiment has been factory calibrated, local disturbances, caused by the individual characteristics of the hull, can only be corrected for by performing an on-scene calibration procedure. As a ship pitches and heaves, it radiates energy into the water in the form of waves. These waves combine with those generated as the ship travels through the water. These ship-generated waves will corrupt local data measurements unless an on-scene calibration procedure is performed.

The calibration of the wave height sensor will involve recording data within a five mile radius of a reference wave height measuring system. The reference for the Two Body Tow-

ing Experiment will be one of the National Oceanic and Atmospheric Administration (NOAA) data collection buoys. There are four of these permanently moored buoys in the vicinity of the Hawaiian Islands as shown in table 6.1 which are operational as of 20 April 1989. Unfortunately, data measured by a NOAA buoy cannot be obtained on a real-time basis. Therefore, no on-scene feedback will be available and all corrections must be done after the experiment.

Table 6.1 NOAA Buoys near the Hawaiian Islands

buoy	Latitude	Longitude	Location
51001	23.4° N	162.3° W	NW of Oahu
51002	17.2° N	157.8° W	SW of Oahu
51003	19.2° N	160.8° W	W of Oahu
51004	17.5° N	152.6° W	SE of Oahu

6.1.2 Procedures

Since the waves generated by the tow can be considered to have no influence on measurement from the tug due to the wide separation between vessels, only the tug is required for this calibration procedure. The ship will be required to maintain a constant course and speed in the close proximity to the designated NOAA buoy for roughly 30 minutes during each data collection run. Since the calibration of the wave height sensor is known to be a function of wave encounter frequency, relative heading of the waves, and ship's speed, measurement will be required at five different relative wave angles (000, 045 or 315, 090 or 270, 135 or 225, and 180) and three different speeds (3, 6, and 9 knots) to obtain a complete data set.

Primary data collection will be performed using instrumentation installed specifically for this experiment. However, to afford a measure of redundancy, it is requested the SALVOR's navigation team assist in the data collection effort. Table 6.3 presents a summary of the data to be recorded during this calibration procedure including the frequency of measurement and responsibility for data collection. Enclosure (2) is provided to assist in manual data collection.

Table 6.3 Required Data Collection for Wave Height Sensor Calibration

PARAMETER	INSTRUMENT	FREQUENCY	COLLECTED BY
Wave Height	portable sensor	2 Hz	MIT
Wind Speed	portable sensor ship's sensor	2 Hz 5 min	MIT ARS 52
Wind Direction	portable sensor ship's sensor	2 Hz 5 min	MIT ARS 52
Speed	portable LORAN C ship's pit log	1 min 1 min	MIT ARS 52
Position	navigation fix	10 min + begin & end	ARS 52

6.2 Flux Gate Compass

6.2.1 Overview

Since a magnetic compass, whether mechanical or electronic, is sensitive to magnetic fields, any magnetic disturbance near the compass will deflect it from the proper reading.

Both the permanent and induced magnetism of the ship will influence compass readings and therefore provisions must be made to compensate for these forces. Preliminary compass adjustments can be accomplished pierside to minimize the effects of the inherent magnetic properties of steel and hard iron used in construction of the ship. However, since the induced magnetic signature of the ship is dynamic in nature and varies depending on the ship's location and orientation with respect to the magnetic poles, final compass corrections can only be performed at sea.

6.2.2 Procedure

Magnetic compasses are normally calibrated by comparison to a compass of known deviation through a standard procedure known as "swinging the ship." This involves steaming the ship on various magnetic headings and comparing the compass readings to a reference compass. For the Two Body Towing Experiment, calibration of the flux gate compasses will be accomplished by steaming the ship in known reference directions (typically the eight cardinal and intercardinal headings) and comparing their measured heading with that of the ship's installed magnetic compass. Knowing the deviation of the ship's magnetic compass, the deviation of the flux gate compasses can be computed. This procedure can be done in conjunction with the wave height sensor calibration described above.

The HECTOR will also have an installed flux gate compass which must be calibrated. However, since her installed magnetic compass will not be operational, the SALVOR's magnetic compass must be used as the reference compass for calibration. To use the magnetic compass of one ship to determine the deviation of a compasses on another ship will require intricate ship handling; something that salvage ship drivers have proven experience. The

HECTOR's flux gate compass will be calibrated as the two ships are proceeding out of port to conduct the data collection phase. This will require the tug to maneuver into a position such that the centerline of both the tug and tow are aligned, as visually verified from the tug's pelorus, on each courses used in the tug's flux gate compass correction. At the moment that the tow vessels are aligned, simultaneous recordings of the headings from both flux gate compasses and the tug's magnetic compass will be taken. The reading from the tow will be obtained via telemetry on a real-time basis. Although this will only be a "pseudo" calibration procedure, it is considered accurate enough for purposes of this experiment since we are mainly interested in the time-varying changes in the headings of both vessels while towing.

NAVSEA TWO BODY TOWING EXPERIMENT DATA COLLECTION SHEET

Please complete a separate form for each test run of the experiment

Test Run # ______ Date ________________ Ordered Course ________ Ordered Speed ________

Time	Position Latitude / Longitude	SOG	COG	Wind Speed	Wind Dir.	Ship Speed	Pitch stbd / port	RPM stbd / port	Wave Height
	log every 10 minutes						log all changes		
	/						/	/	
	/						/	/	
	/						/	/	
	/						/	/	
	/						/	/	
	/						/	/	
	/						/	/	
	/						/	/	
	/						/	/	
	/						/	/	
	/						/	/	
	/						/	/	

Enclosure (1) Data Collection Sheet

NAVSEA TWO BODY TOWING EXPERIMENT
CALIBRATION DATA COLLECTION SHEET

Test Run # ______ Ordered Course ______ Ordered Speed ______

Time	**Ship Speed**	**Wind Speed**	**Wind Direction**	**Latitude**	**Longitude**
	every minute	every 5 minutes		begining and end	
		XXXXXX	XXXXXX	XXXXXX	XXXXXX
		XXXXXX	XXXXXX	XXXXXX	XXXXXX
		XXXXXX	XXXXXX	XXXXXX	XXXXXX
		XXXXXX	XXXXXX	XXXXXX	XXXXXX
				XXXXXX	XXXXXX
		XXXXXX	XXXXXX	XXXXXX	XXXXXX
		XXXXXX	XXXXXX	XXXXXX	XXXXXX
		XXXXXX	XXXXXX	XXXXXX	XXXXXX
		XXXXXX	XXXXXX	XXXXXX	XXXXXX
				XXXXXX	XXXXXX
		XXXXXX	XXXXXX	XXXXXX	XXXXXX
		XXXXXX	XXXXXX	XXXXXX	XXXXXX
		XXXXXX	XXXXXX	XXXXXX	XXXXXX
		XXXXXX	XXXXXX	XXXXXX	XXXXXX
				XXXXXX	XXXXXX
		XXXXXX	XXXXXX	XXXXXX	XXXXXX
		XXXXXX	XXXXXX	XXXXXX	XXXXXX
		XXXXXX	XXXXXX	XXXXXX	XXXXXX
		XXXXXX	XXXXXX	XXXXXX	XXXXXX
				XXXXXX	XXXXXX
		XXXXXX	XXXXXX	XXXXXX	XXXXXX
		XXXXXX	XXXXXX	XXXXXX	XXXXXX
		XXXXXX	XXXXXX	XXXXXX	XXXXXX
		XXXXXX	XXXXXX	XXXXXX	XXXXXX
				XXXXXX	XXXXXX
		XXXXXX	XXXXXX	XXXXXX	XXXXXX
		XXXXXX	XXXXXX	XXXXXX	XXXXXX
		XXXXXX	XXXXXX	XXXXXX	XXXXXX
		XXXXXX	XXXXXX	XXXXXX	XXXXXX

Enclosure (2) Calibration Data Collection Sheet

Thesis
C44922 Christensen
c.1 Plans and specifications for a full-scale towing model validation experiment.